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Next-Generation Driver Information Systems

FACULDADE DE CIÊNCIAS
UNIVERSIDADE DO PORTO

MAP-i Doctoral Programme in Computer Science
University of Minho, Aveiro and Porto
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To my family and friends.

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Pedro Gomes,

June, 2014

Abstract

The vehicular transportation is one of the most important means of transportation in the world. Hundred of millions of people in the world use a car, a bus or any kind of road vehicle to go to work every day. Vehicular transportation is also one of the most used means of transportation of goods. With the evolution of the society, we have seen a considerable growth of the number of motor vehicles. This growth led to several negative effects: first on the increasing number of road traffic injuries, which has become a global health problem; and second, on the rising costs of developing and maintaining the road infrastructures. Automotive industry equips modern vehicles with sophisticated assistance systems. However, these systems rely on the information retrieved by the vehicle itself using radars and cameras, which only provides partial information of the vehicle's surroundings. Vehicular ad hoc networks enable innovative and more informed intelligent transportation systems that can help to tackle the problems of vehicular transportation. This thesis aims to deliver innovative driver information systems based on the of vehicular communications. The work of this thesis is divided in three different categories: safety; sustainability; and simulation. Regarding safety in vehicular transportation, we propose an overtaking assistance system based on vehicle-to-vehicle communication, video-streaming and augmented reality that introduces the concept of the virtual windshield. We propose an assistance system that explores this concept for delivering information about the topology of the network on the windshield in order to avoid road accidents in low-visibility situations. Furthermore, we propose an audible augmented reality assistance system, that uses vehicular communications to trigger an audible event on the sound system of a vehicle. We propose two different systems based on advertising that focus on achieving sustainability of the road infrastructure and transportation systems. Finally, we provide a driving simulation framework for testing driver information systems based on vehicular communications. Results show that vehicular communications enable a new type of solutions to increase safety in vehicular transportation, and that augmented reality in vehicular environment is indeed effective. Moreover, they show that vehicular ad hoc networks provide means for achieving sustainability of transportation systems and road infrastructures. Finally, this thesis show that a driving simulator integrated with a traffic simulator is the perfect framework to design, evaluate and test driving information systems.

Resumo

O transporte veicular é um dos mais importantes meios de transporte no mundo, com centenas de milhões de pessoas no mundo a usarem diariamenge o carro, autocarro ou outro tipo de veículo de estrada para se deslocarem para o trabalho. O transporte veicular é também um dos meios mais usados para transporte de mercadorias. Com a evolução da sociedade, temos assistido a um crescimento considerável de veículos motorizados. Este crescimento provocou vários efeitos negativos: primeiro no crescimento do número de feridos provocados por acidentes rodoviários, o qual se tornou num problema de saúde global; e em segundo, os crescentes custos do desenvolvimento e manutenção da infra-estrutura rodovíaria. Atualmente, a indústria automóvel equipa os carros com avançados sistemas de auxílio ao condutor, mas no entanto estes baseiam-se em informação recolhida pelo veículo em si, usando radares e câmaras, os quais só fornecem uma parte da informação da vizinhança. As redes veiculares permitem o aparecimento de sistemas de transportes inteligentes inovadores e mais informados que ajudam a resolver os problemas do transporte veicular. Esta tese tem como objetivo fornecer sistemas de informação para o condutor baseados em comunicações veiculares. O trabalho desta tese está dividido em três diferentes categorias: segurança; sustentabilidade; e simulação. Relativamente à segurança, propomos um sistema de auxílio à ultrapassagem baseado em comunicação veículo-a-veículo, transmissão de vídeo e realidade aumentada, que introduz o conceito de pára-brisas virtual. Propomos um sistema de auxílio ao condutor que explora este mesmo conceito para mostrar informação da topologia da rede no pára-brisas com o intuito de evitar acidentes rodoviários em situações de fraca visibilidade. Também é proposto um sistema de auxílio ao condutor com base em realidade aumentada sonora, que usa comunicações veiculares para despoletar um evento sonoro no sistema de som do veículo. Propomos dois sistemas diferentes baseados em publicidade que se focam na sustentabilidade da infra-estrutura rodoviária e sistemas de transportes. Finalmente, fornecemos uma ferramenta de simulação de condução para testar sistemas de informação para o condutor baseados em comunicações veiculares. Os resultados mostram que as comunicações veiculares permitem um novo tipo de soluções para aumentar a segurança no transporte veicular e que a realidade aumentada é realmente eficaz no ambiente veicular. Além disso, mostram que as redes veiculares fornecem meios para alcançar a sustentabilidade de sistemas de transportes e infra-estruturas rodoviárias. Finalmente, esta tese mostra que

um simulador de condução integrado com um simulador de trânsito é a ferramenta perfeita para desenhar, avaliar e testar sistemas de informação para o condutor.

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Acronyms

AASHTO American Association of the State Highway and Transportation Officials

ABS Anti-lock Braking System

ACC Adaptive Cruise Control

ADAS Advanced Driver Assistance Systems

ANN Artificial Neural Network

API Application Programming Interface

AR Augmented Reality

AU Application Unit

C2C-CC CAR 2 CAR Communication Consortium

CAM Cooperative Awareness Message

CCH Control Channel

CHMSL Center High Mounted Stop Lamps

CLOD Continuous Level Of Detail

CVCAM Computer Vision Aided Cooperative Awareness Messages

DIS Driver Information Systems

DSRC Dedicated Short Range Communications

EDCA Enhanced Distributed Channel Access

EEA European Economic Area

ESC Electronic Stability Control

ESP Electronic Stability Program

ESS Emergency Stop Signal

EU European Union

FARS Fatal Analysis Reporting System

FCC Federal Communications Commission

FCUP Faculdade de Ciências da Universidade do Porto

FEC Forward Error Correction

GDP Gross Domestic Product

GPS Global Positioning System

GUI Graphical User Interface

HCI Human Computer Interaction

HMI Human Machine Interface

HUD Head-up Display

IDM Intelligent Driver Model

INIR Portuguese Road Infrastructure Institute

ITS Intelligent Transportation Systems

LBO Light Blue Optics

LCD Liquid-Crystal Display

LOD Level Of Detail

LOS Line-of-sight

LTE Long Term Evolution

MAC Media Access Control

MANET Mobile Ad Hoc Network

MBMS Multimedia Broadcast Multicast Services

MVS Making Virtual Solid, LLC

NLOS Non-line-of-sight

OAAA Outdoor Advertising Association of America

OBU On-Board Unit

OpenCV Open Source Computer Vision Library

OSG OpenSceneGraph

P2P Peer-to-Peer

PND Portable Navigation Devices

PPP Public-Private Partnerships

PSNR Peak Signal-to-Noise Ratio

PTL Physical Traffic Lights

QOE Quality-of-Experience

ROI Region Of Interest

RS Random Stands

RSC Random Stands Cluster

RSU Road-side Units

RTM Road Trench Model

RTP Real Time Protocol

SCH Service Channel

SS Sorted Stands

SSC Sorted Stands Cluster

STS See-Through System

TCP Transmission Control Protocol

USA United States of America

UTC Coordinated Universal Time

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V4L Video4Linux

VANET Vehicular Ad Hoc Network

VNS Vehicular Networks Simulator

VSS Virtual Surround Sound

VTL Virtual Traffic Lights

WAVE Wireless Access in Vehicular Environments

WLAN Wireless Local Area Network

WSN Wireless Sensor Network

ZOR Zone of Relevance

Chapter 1

Introduction

Next-generation driver information systems will increase road safety by helping drivers become better aware of the road and its potential hazards. Since the appearance of the motor vehicle, the vehicular transportation has been one of the most important means of transportation in the world. Every day, hundred of millions of people travel by car, bus or other kind of road vehicle to go to work. Furthermore, it has been the basis for goods transportation in the world. In 2010, the estimate of motor vehicles in the world was of 1 billion [4] and in 2020 it should reach 2 billion vehicles [5, 6]. The negative effects of these numbers are an increase on road traffic injuries and rising costs of road infrastructures maintenance. Injuries caused by road traffic accidents are usually tolerated as an inherent risk of driving, even though these accidents caused over 1.24 million deaths in 2012 [7]. This problem is not confined to developed countries but it has rather become a global health and development problem of epidemic proportions. To face this, the automotive industry is equipping vehicles with relevant sophisticated electronic assistance systems. Advanced Driver Assistance Systems (ADAS) such as adaptive cruise control [8], lane departure warning [9], night vision and pedestrian detection [10], adaptive light control [11], traffic sign recognition [12] or blind-spot detection [13], are already available in many production cars. Currently, most of these systems rely on the information retrieved by the vehicle itself, provided by radars or cameras. While these systems are useful, they lack information and/or contextualization regarding the vehicle's surroundings.

Recent advances in wireless technologies offer new possibilities for Intelligent Transportation Systems (ITS). In particular, the new Dedicated Short Range Communications (DSRC) standard [14], coupled with the emerging Vehicular Ad Hoc Network (VANET), has the potential to efficiently support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. Thus, it enables a variety of applications for safety, traffic efficiency, driver assistance, and infotainment. Extensive research has been made on traffic efficiency and routing protocols using VANET simulators. Moreover, the scientific community proposed several V2V and V2I applications. However, most of research in VANET has been focused on solving technological issues regarding the network itself, disregarding the point-of-view of the driver in the network and VANET-enabled applications. This lack of driver-centric point-of-view in applications is a flaw that needs to be addressed by the research community. The automotive industry always addressed this issue by exhaustingly testing each new information/assistance system that is introduced in a vehicle. Although these new intelligent systems can support the driver, they can also do harm if message delivery becomes excessive, compromising the driving task. Providing these systems with a driver-centric perspective, capable of coupling a wide range of new technologies, is essential towards the improvement of the driver's performance, comfort and safety, as it allows the driver to take the best out of in-vehicle technology. Recently, Augmented Reality (AR) has been introduced in vehicles, making it possible to display all types of information in front of the eyes of the driver and reducing his distraction. By coupling vehicle's communication capabilities and its AR capabilities, we are able to provide the driver with more efficient and informed systems.

Safety and efficiency in vehicular transportation depends not only on the vehicle's itself and its capabilities but also depends on an efficient road network. The burden associated with the costs of maintaining the road infrastructure has grown exponentially with the increase of motor vehicles. Furthermore, the costs associated with time spent on traffic jams caused by an inefficient road network or with accidents caused by the degradation of roads are a reason for concern in modern societies. These problems are caused by the difficulty to achieve sustainability of transportation systems caused by the lack of investment on road networks. VANETs can help achieving this sustainability by providing information that make the road network more efficient. However, efficiency is only one part of the sustainability problems. Currently, the road infrastructure funding relies mostly on national budgets or on tolls paid by the user. We envision that using an advertising funding scheme based on VANETs, we can increase the sustainability of the road infrastructure and easy the costs to the user, similar to the Internet website's sustainability.

The overall goal of this work is to create innovative driver information systems that provide the driver with more informed systems relying on information that comes from VANET. This work makes extensive use of AR in the vehicular environment, introducing the concept of the virtual windshield.

1.1 Contributions

Modern vehicles are equipped with all sorts of technology equipments and with the advent of VANET there is a technology gap that needs to be explored. This thesis explores this gap by coupling VANET with the AR capabilities of modern and future vehicles, creating the concept of the virtual windshield. The following contributions were produced:

- Since current ADAS are based on information provided by the vehicle itself, we explore the lack of information about neighbouring vehicles by using V2V communication. We designed, implemented and prototyped the See-Through System (STS), an overtaking assistance system that makes use of V2V communication and real-time video streaming to assist the driver with the overtaking task, one of the most dangerous driving tasks [15, 16, 17, 18].

- Based on the concept of the virtual windshield, used by the STS, we introduce a cooperative awareness system that merges the information provided by the VANET and the information gathered by computer vision enabled cameras. Even on partial deployments, this system is able to provide the driver with information about its surroundings. This awareness is particularly useful on rough weather conditions, such as dense fog or rain.

- We introduced a new concept with the Virtual Surround Sound (VSS). This system makes usage of V2V communication and the currently installed sound systems to provide the driver with an audible awareness of his surroundings.

- We designed a completely new scheme for funding the road infrastructures based on advertising and the concept of virtual windshield [2]. We envision the usage of V2V communication to connect to an advertising network to display advertisements to the driver in order to achieve sustainability in roads.

- We proposed an advertising distribution platform for providing sustainability for public transportation systems. This platform is hybrid, using cellular communication to deliver new advertisements for a small number of vehicles and V2V communication to distribute these advertisements to the rest of vehicles.

- We designed a driving simulator to test and evaluate innovative ADAS and ITS applications [19]. In order to test all types of scenarios, this driving simulator was coupled with a VANET simulator. This simulation framework was used to test and evaluate several STS iterations before making road experiments. Furthermore, it was used to evaluate a Graphical User Interface (GUI) for the Virtual Traffic Lights (VTL) [20].

1.2 Structure

The remainder of this thesis is organized as follows. Chapter 2 gives a background of the evolution of automotive systems since the appearing of the motor vehicle. Chapter 3 gives an overview of VANETs and its applications. Chapter 4 presents the VANET-enabled safety systems. Chapter 5 presents the intelligent transportation systems developed based on the information provided by VANET. Chapter 6 describes the simulation framework that was developed to test the applications developed on this thesis. Finally, Chapter 7 discusses the conclusions of the proposed work and the guidelines for the future work.

Chapter 2

Background

Modern society urges for efficiency of vehicular transportation, both on safety and costs. The automotive industry has been investing a lot of resources on making vehicles safer and more efficient. Furthermore, scientific community has been focused on traffic efficiency and vehicle safety and information systems. This chapter gives a background on the evolution of applications within vehicular transportation.

2.1 Automotive Systems

Since the beginnings of the automotive industry that vehicles are being equipped with all sort of systems to help the driver with the driving task. In the early 1900s, electric horns were introduced in vehicles. This enabled different types of horns, for an example, ambulances, police cars and fire-fighter's trucks to be equipped with horns that play a specific sound audible by other drivers warning their emergency status. Motor vehicles have a windshield to protect the driver from harsh winds. The placement of windshields in the vehicle's front led to the invention of windshield wipers. In their first version, these wipers were manual, the driver and/or the passenger needed to manually activate them. In 1920s electrical wipers were introduced, and consequently intermittent wipers appeared in 1970s. Several different types of wipers are used by different automotive manufacturers. Most of them use two wipers, one in front of the driver and the other in front of the passenger. Some manufacturers try to maximize the area affected by the wipers in order to give the driver a better and clean perspective of the road. Recently, rain sensing wipers were introduced and are slowly becoming the standard in modern vehicles.

The modern vehicle's lighting system is the result of several evolutions that began with the introduction of front and rear lamps. Headlamps provide the visibility needed by the driver to safely pursue with the driving task in low-light situations, while rear lamps help the other drivers by making each vehicle visible in such situations. Xenon lights were introduced in headlamps in order to increase this visibility. Nevertheless, traditional headlamps cannot clearly illuminate corners of a curve. Therefore the automotive industry proposed directional headlamps, where the driver can see his way through curves. The stop lights placed in the rear of the vehicle warn other drivers that the braking system of the vehicle is activated. Recently, the Center High Mounted Stop Lamps (CHMSL) became default on vehicles, which not only helps to differentiate the stop light from normal read headlamps, but also helps the other drivers see-through the windows the braking system activated and avoid possible crash situations. Furthermore, fog lamps help the driver to overcome low-visibility situation such as dense fog. Blinking turn signals were introduced to signal the change of direction to other drivers. Emergency Stop Signal (ESS) was also introduced by several manufacturers to highlight an emergency braking situation.

Safety has been one of the most focused areas by the automotive industry. The introduction of safety belts in 1950s had a huge impact on deaths by crashes all over the world. The use of safety belts avoid serious injures by keeping both driver and passengers inside the vehicle cockpit. First safety belts had 2 endpoints, but they evolved to the Y-shaped 3 endpoint safety belts used in current vehicles. Furthermore, the current standard safety belt have pre-tensioners that prevent the occupant to lean forward when a crash occurs. First braking systems relied on a drum, with an internal shoe brake that expanded to the drum inner walls and brake the vehicle. Until 1918 all braking systems were mechanical, afterwards hydraulic-brake systems slowly became the common standard to activate the breaks in all the four wheels. However, hydraulic drum brake systems have issues regarding the heat that cause malfunctioning when constantly used. Therefore in 1950s the automotive industry began installing the braking discs, being the current standard on modern vehicles. Since then only some improvements have been made, by introducing ventilated discs and the Anti-lock Braking System (ABS). Recently in 1990s, the Electronic Stability Control (ESC) or Electronic Stability Program (ESP) was introduced by automotive manufactures and rapidly became one of the most important active systems regarding vehicle's safety. The ESC's computer unit detects if the vehicle has lost steering control and uses the brakes to give back stability to the vehicle.

With the evolution of technology, systems introduced in modern vehicles are becoming more intelligent and advanced. Modern vehicles are equipped with all sorts of advanced systems that will be highlighted in the next section.

2.2 Advanced Driver Assistance Systems

In the last decades, a lot of effort has been put into developing innovative ADAS to enhance driving safety and comfort [21, 22, 23]. For example, some radar-based approaches intend to lower road accident risk despite low visibility, identifying road vehicles and obstacles [24, 25]. Different crash avoidance systems focus on forward collision warning [26], intersection [27], blind-spot [13] and lane change warning systems [9]. These systems consist of sensors that provide the vehicle with 360 degree awareness [28, 29].

The balance of accidents related to overtaking manoeuvres represent between 10 and 15 % of the total percentage of road accidents [30, 31, 32]. Different studies have shown that, generally speaking, it is a challenge for drivers to estimate the time required to complete the overtaking manoeuvre until the oncoming vehicle arrives. This could be due to an inaccurate visibility of the road [33] or difficulties in interpreting the distance to the oncoming traffic [34]. The scientific community has proposed some overtaking assistants based on warning signals that inform the driver about the danger of starting an overtaking manoeuvre. They consider factors like existence of curves, inclination of the road or bad visibility, for example accessing the data stored in maps from navigations systems for calculating vehicle's positions and accessing information related to the vehicle motion and road architecture [35, 36]. Other systems give feedback based on data collected from monitoring the driver before and during overtaking [37]. However there is some research concerning calculations related to the distance to the oncoming vehicle [38]. Wireless technology based on VANETs can provide the driver with additional tools to solve this problem.

Direct wireless communication is also used for vehicles to share information in vehicular ad hoc networks thus transmitting information from one vehicle to surrounding vehicles [39, 40, 41]. An example of applicability of information transmission through VANET was shown in [36], where a protocol for locating a car with vision sensors was proposed. Most technological approaches use a large spectrum of sensor information and combine several methods for object or pedestrian detection and the classification in object types [42, 43]. In addition systems based on artificial vision have been suggested to summarize information about vehicle's environment such as road, traffic, and traffic signs [44]. Also the role of image-based ADAS for different applications using built-in cameras to assist the driver was studied with different approaches [45, 46]. The use of wireless technology based on VANETs for information exchange to reduce road accidents is especially promising in this context, especially if this information is presented as a video image. VANET based video streaming technology research has been conducted in recent works. [47] proposed an architecture for video streaming to V2V communication with multiple receivers able to handle connection problems in the V2V network related to vehicle's radio range and connection lifetime, both typical issues of the dynamic condition of vehicles [48, 49]. Following with problems related to the transmission of data associated to vehicular networks, [50] presented a distribution of visual information based on network coding that can solve potential packets corruption or loss, thus allowing a faster transmission of video files. In [51] the authors presented a system that allows drivers to see objects in motion through opaque buildings and road intersections with low visibility. The same authors present a prototype based on augmented reality and the combination of images captured by several cameras that provide the view of the driver and the view of what is behind the opaque surface. An effect of transparency is achieved combining the layers of both images.

2.3 Computer Vision

Computer vision in the context of vehicles has been a very active topic in ITS for the last two decades [52]. The automotive industry is increasingly equipping vehicles with windshield cameras that provide data to computer-vision-based systems. Some examples of these systems are automatic car following, object classification and vehicle detection and tracking [53, 54]. Image-based object detection methods have been proposed in various research projects. In some cases, synchronized cameras were combined to extend the number of parameters like camera shot angle or camera focal length combining visual fields in the image-based object detection [55]. The authors in [56] conducted an exhaustive review about the most recent vision-based vehicle detection systems that use cameras mounted on the vehicle. The visual processing of those detection systems is based on vision algorithms that focus for example on neural networks, temporal-spatial modelling and fuzzy logic and are useful in the context of the visual-based vehicle guidance for applications such as road following or traffic sign recognition [57]. In this context, the authors in [58] presented a shape-based object detection method based on distance transforms where object shapes are captured and classified and used for real-time vision on-board vehicles. Related to this, calculation approaches to obtain the distance between the driven car and the vehicle ahead can vary depending on the technology that is used to develop the algorithm.

The precise localization of the vehicles involved in the overtaking manoeuvre is crucial to perform the coordinate transformation of the video between the vehicles. While cooperative localization is an important technique used for this purpose in Wireless Sensor Network (WSN) [59], the specific characteristics of the overtaking assistant make visual odometry [60] a more suitable technique for obtaining the precise distance between the two vehicles.

Vision-based driver assistance systems for the overtaking manoeuvre require a low data transmission delay to achieve a reliable detection of vehicles coming from the opposite direction. Thus, it is important to obtain motion estimation against image noise, to detect the image. In this context, the authors in [61] developed a robust detection method based on variable bandwidth density fusion.

2.4 Augmented Reality

Augmented reality on the windshield exists even prior to the invention of electronic displays. The rear-view mirror centrally placed on the windshield has been invented to augment the forward-looking perspective of drivers with rear-view images, improving safety as a result of improved perception. Some people might argue that such a purely optical system cannot be considered as an AR system, as it lacks the integration of computer-generated elements with the real world environment. In fact, modern rear-view mirrors can already be fitted with electronically-controlled auto-dimming features, which is technically an electronic based manipulation of a real-world reflection. Furthermore, some side mirrors already superimpose visual alerts when a vehicle is detected in the driver's blind-spot [62]. Nowadays, augmented reality ADAS systems are pervasive in most vehicles and not just high-end models. Other visual AR include front-facing and rear-facing cameras that provide enhanced vision, lane detection, pedestrian detection and even parking assist. Note that for the latter, it is more common to find acoustic AR solutions, where ultrasound proximity detectors provide audio cues in the form of beeps with periodic intervals proportional to the obstacle distance.

Navigational information has also benefited from the development of AR. This can be seen with the evolution of Global Positioning System (GPS) navigators. Traditional Portable Navigation Devices (PND) were originally fixed onto the windshield and presented the driver with two-dimensional maps which included directions in relation to the route to follow. More advanced PND devices merged a video stream of the road captured by a forward facing camera on the device with pictographic content created digitally, conveying the navigational information as video see-through AR. The evolution of the technology used to impose the GPS navigator content over the field of view of the driver is illustrated in Fig. 2.1.

The earliest units used the windshield to stick a portable electronic display that obscured the driver's vision (Frame A). To solve this problem, some systems use a video camera on the back of the portable device that captures the front scenario and merges navigational images with the real-time video streamed from this camera, configuring what is know as AR video see-through technology [63] (Frame B). In modern high-end vehicles, the windshield is actually used as a transparent canvas over which the navigational images are projected, configuring what is know as AR optical see-through technology [63] (Frame C). Since then the display of navigational information has evolved to become more embedded on the windshield, where the information is directly superimposed as optical see-through AR. Recent innovations have focused on ways to present this navigational information to the driver in more natural and safer ways, providing the driver with a sense that the information is part of the real world. In addition to the displays for navigational information, some instrument consoles include an embedded screen that displays the view from a vehicle-mounted infrared or thermal camera, implementing a night vision driver assistance system [10], capable in some cases of identifying

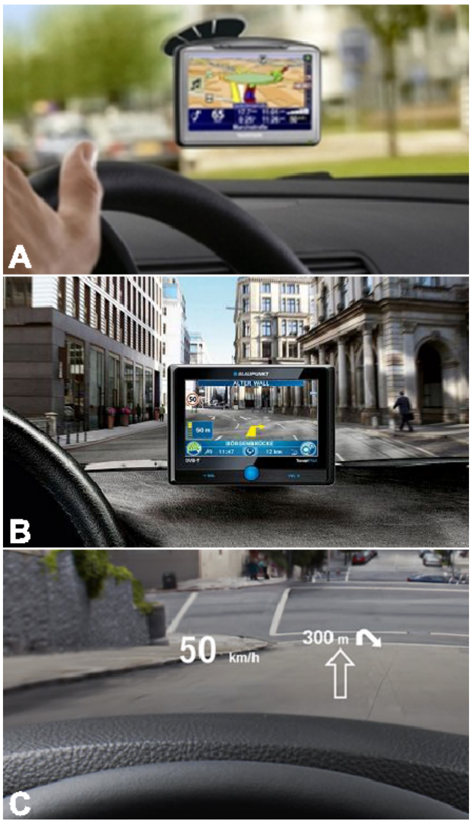

Figure 2.1: Evolution of the technology used to impose the GPS navigator content over the field of view of the driver.

and highlighting pedestrians. The idea is that these small screens can augment the perception of drivers when the visibility through the windshield is low, in a similar fashion to rear-view mirrors.

Systems that explore the concept of virtual transparency have also been subject of study in recent years. In [51] the possibility of seeing through occluding surfaces is explored by means of video captured by several cameras. This is achieved by combining the information captured by a fixed camera viewing the occluded area with that of a camera viewing the occluding surface, thus making it possible to see through it. Similarly, a wall see-through system for drivers has been examined in [64]. This safety system provides visibility to the driver at intersections with blind corners, where for example vehicles are occluded by walls. The authors compare several levels of visualization based on the amount of information they present to identify the minimum information needed for the driver to predict a crossing collision.

In [65], the authors present a system that can also overlay 3D virtual elements in the same context as the driving scenario. This system is able to create a simplified model of the road scene. This model, known as the Road Trench Model (RTM), provides reference coordinates used to present the virtual information. The RTM captures information about the geometry, lighting and other attributes of the real world road scene which is then used to accurately apply shading and shadowing to the virtual content according to the vehicle's position. The authors suggest that this model would provide the support for the display of virtual stop signs at road intersection or virtual billboards. Using VTL created as AR objects on the windshield, the authors in [66] have proposed a novel self-organised traffic control paradigm, powered by V2V communications.

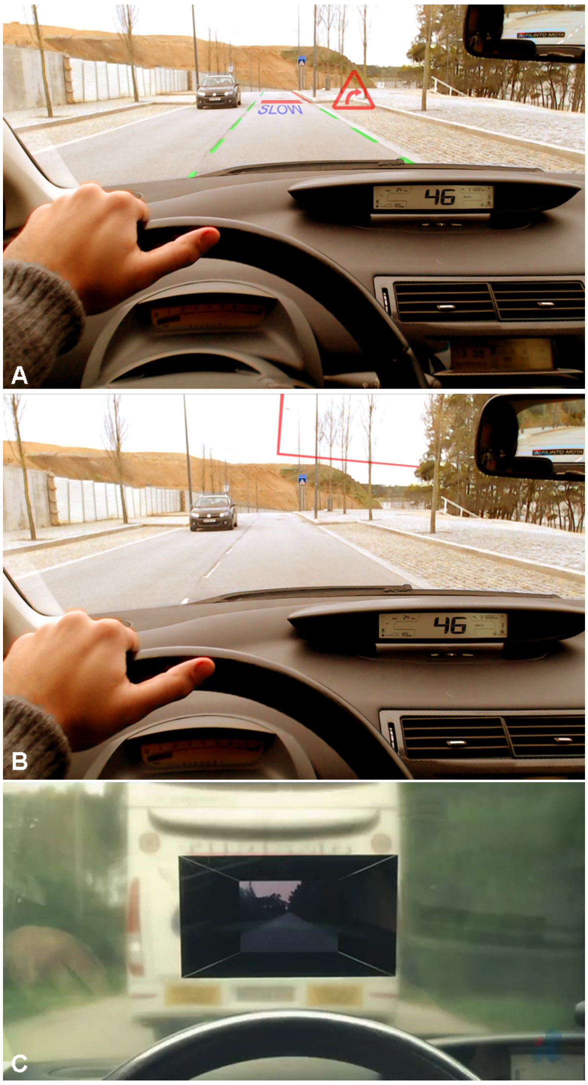

Figure 2.2: Augmented reality in the vehicular environment.

Optical see-through AR in the context of driving has the major advantage of allowing the augmented content to be superimposed over a very large and ideally placed screen, which is the glass-based virtual windshield. Laser holographic projection is an emerging technology being applied in this context. The company Light Blue Optics (LBO) has been developing laser-based virtual image displays capable of displaying high brightness signage at high resolution and in full-colour [67, 68]. LBO's laser projection engine explores the process of two-dimensional diffraction to create pictograms that are always in-focus and can be projected on curved surfaces, such as a windshield. A preview of the pictography that can be displayed on a windshield using LBO technology is shown in Fig. 2.2A. Another example of an augmented reality system also based in laser projection is the Virtual Cable system, being developed by the company Making Virtual Solid, LLC (MVS) [69]. The idea is to have navigation information being displayed to the driver in the form of a virtual 3D cable that appears to be hanging over the road, providing a guideline that the driver just has to follow to reach the destination. Figure 2.2B provides a snapshot of the functioning of this Virtual Cable. Optical see-through AR can also be implemented through transparent Liquid-Crystal Display (LCD), embedded in the windshield. Figure 2.2C shows a snapshot of the functioning of STS implemented using a transparent LCD [16].

High-end vehicles already combine video and acoustic AR for parking assist, such as the surround view from BMW that provides a 270° birds-eye-view by combining the rear-facing camera vision with the cameras mounted under the side mirrors [70]. The surround view also includes the audio cues as well as the computer vision generated parking guidelines. The Lexus cars feature rear and side parking assist monitors that help eliminate blind spots as drivers park their vehicles [71]. These systems provide real-time images of the areas directly behind and to the side of the vehicle and are captured through cameras mounted above the license plate (in the case of the rear parking assist) and under the passenger side mirror (in the case of the side parking assist). The images are displayed either on the multi-display screen located in the centre console of the vehicle or on a small monitor incorporated in the rear view mirror. Lane departure warning systems also use different Human Machine Interface (HMI) approaches to warn drivers of possible unintentional lane crossings [9]. For instance, Volvo employs audio cues similar to the parking assistance cues, while BMW combines visual warnings in the console with a vibration in the steering wheel. Note that the latter recreates the sensation provided by rumble strips that commonly delimit road lanes in many highways. This is an example of the tactile AR that is already present in current motor vehicles.

Several manufacturers have presented augmented reality glasses that can also be used to create the driver's augmented vision of the road. These have some important advantages that results from the wearable nature of such equipment: while eye-point alignment calibration or eye-tracking systems are typically necessary with windshield-based AR technology, wearable displays overcome this problem by their very nature. Nonetheless, their drawbacks are the need to wear glasses while driving and the still limited resolution achieved by these very small displays.

Chapter 3

Vehicular Ad Hoc Networks

VANETs have gathered considerable attention from the research community and the automotive industry. A VANET is a particular case of a Mobile Ad Hoc Network (MANET), that provides inter-vehicular communication between nearby vehicles and communication with Road-side Units (RSU). It provides the means to support new advanced safety and infotainment applications within the vehicular environment. Specially, the DSRC offers the potential to support V2V and V2I communications.

A VANET is unique compared to other MANET. The topology changes rapidly, which frequently causes network fragmentation. Furthermore, the network diameter of a VANET is effectively smaller than other type of MANET. The high mobility of vehicles is the cause of the frequent changes of the topology of the network. Thus only allowing for a short period of time in which a communication link can be established between two vehicles. The high speed at which vehicles travel causes VANETs to have a short lived communication link. For an example of two vehicles in opposite directions, this link will have a very small period of time. The poor connectivity caused by the high mobility of the vehicles results on a small diameter of the network. Therefore, it is not practicable for a vehicle to store the complete network topology. This is one of the problems that research has been dealing with when trying to apply existing routing algorithms to VANETs. The high mobility of the nodes in a VANET and its low predictability propose as a problem to existing routing algorithms to transmit a message with a multi-hop path. In VANETs, vehicles typically store a location table with their one-hop neighbours, and geographical location of a node plays a big role on a VANET.

This chapter gives an overview on the architecture of a VANET, namely on DSRC and its applications. Furthermore, we give an introduction to the deployment of a testbed in the city of Porto and to the DSRC radios used both on this testbed and on the work of this thesis.

3.1 Architecture

We consider the architecture proposed by CAR 2 CAR Communication Consortium (C2C-CC) as the reference in VANET [72]. Figure 3.1 depicts this architecture. C2C-CC's architecture defines three different domains: in-vehicle; ad hoc; and infrastructure.

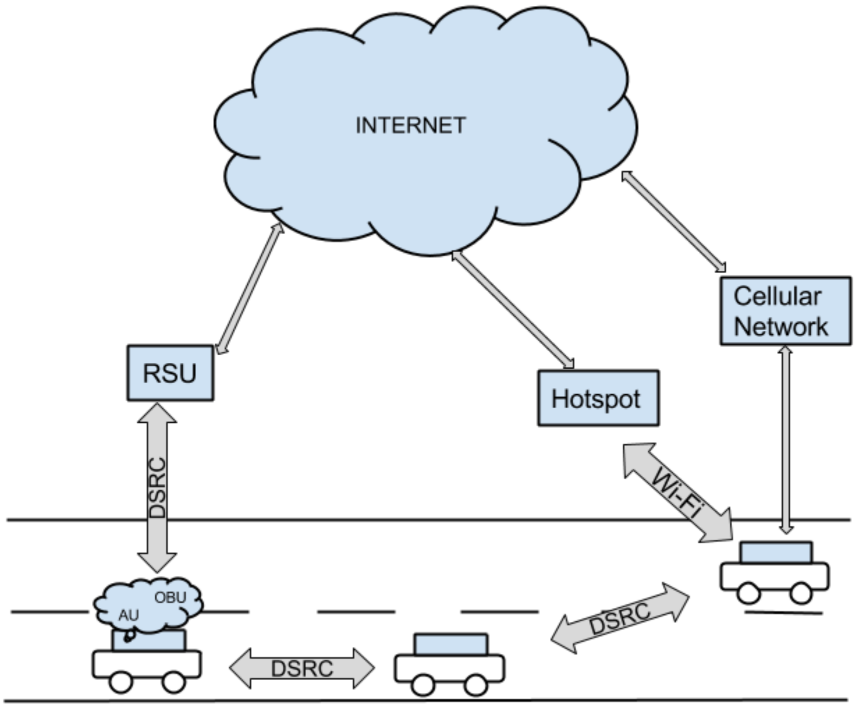

Figure 3.1: C2C-CC proposed architecture.

The in-vehicle domain consists of the local network installed inside each vehicle. This domain consists on two different type of units: an On-Board Unit (OBU); and an Application Unit (AU). The OBU is a device that provides communication capabilities to the vehicle. Each OBU is equipped with at least one DSRC device, namely a 802.11p compliant radio [14] the current standard for vehicular communications. An AU is responsible for the execution of a set of applications that make use of the communication capabilities of the OBU. The AU can be a portable device that connects to the OBU or can be integrated as part of the vehicle and permanently attached to the OBU. This distinction between OBU and AU can be logical or physical. Typically, these units will integrated in the same device installed in a vehicle.

The ad hoc domain is the network formed by the vehicles represented by their OBUs and the RSUs placed along the road. OBUs and RSUs form an ad hoc network, where they stand as mobile and static nodes, respectively. This ad hoc network can be summarized as the visible part of a VANET. OBUs communicate with RSUs, which can be attached to an infrastructure network that can also be connected to the Internet. Moreover, RSUs can communicate between them, directly or via multihop, and extend the communication range of the connected OBUs, see Fig 3.2 a). Figure 3.2 b) illustrates that RSUs can also transmit new information to the OBUs. OBUs can access Internet through the RSUs or through Wi-Fi hot spots, see Fig 3.2 c). Furthermore, an OBU can be equipped with cellular communication capabilities.

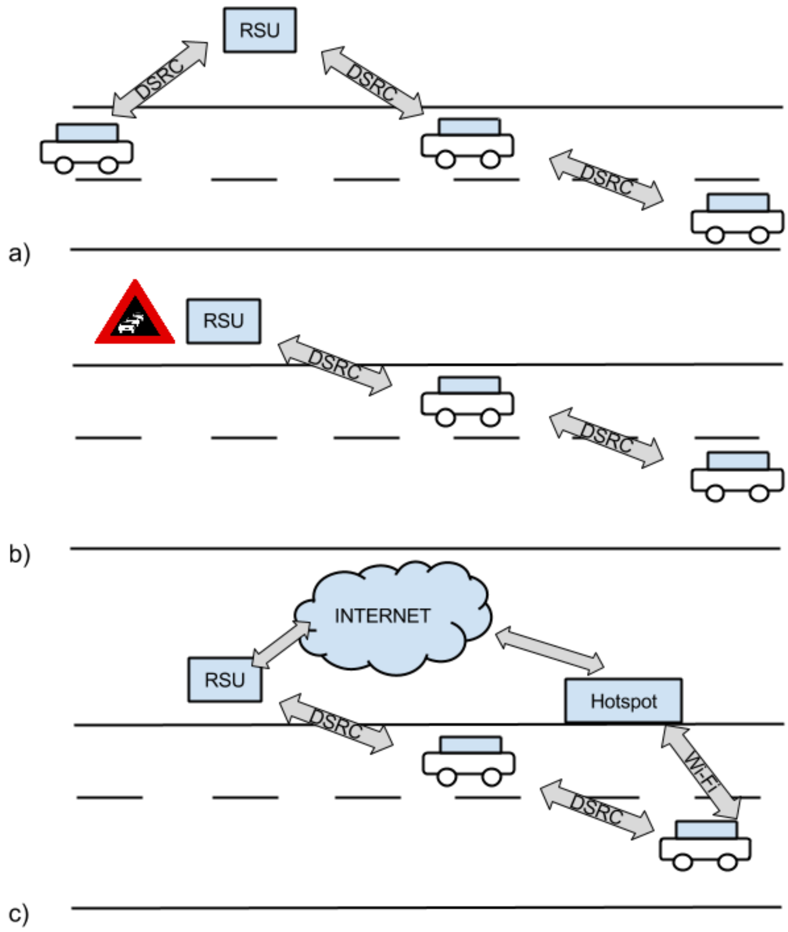

Figure 3.2: Ad hoc domain examples.

C2C-CC defines that the infrastructure domain comprises Wi-Fi hot spots and the RSUs. The difference between them is that RSU are under the domain of road administrators. While, Wi-Fi hot spots can be public or private, their domain can vary and they may have different control access.

Figure 3.3 shows the architecture of the communication layers of an OBU as defined by C2C-CC in their manifesto [72]. They cover three different type of wireless technologies:

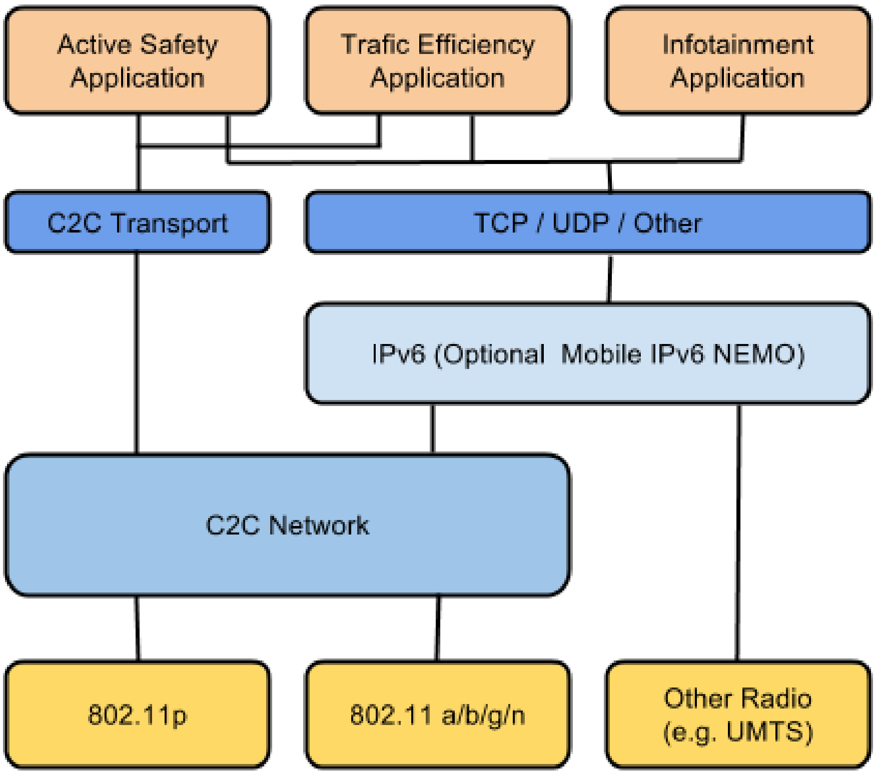

Figure 3.3: C2C-CC communications layers' architecture.

802.11p; 802.11 a/b/g/n; and other radio technologies such as UMTS. The 802.11p [14] is a standard that was specifically designed to provide Wireless Access in Vehicular Environments (WAVE). It was developed to meet the requirements of DSRC.

3.2 Dedicated Short Range Communication

DSRC is specifically designed to support a variety of applications based on vehicular communication. The first generation of DSRC operates using the 915 MHz band and has a limited transmission rate of 0.5 Mb/s. It is mostly used for electronic toll collection. The second generation of DSRC operates on the 5.9 GHz band and transmission rates range goes from 6 to 27 Mb/s. In 1999, the United States of America (USA) allocated 75 MHz of the spectrum in the 5.9GHz band [73] dedicated to this type of communications, while in 2008 the European Union (EU) allocated 30 MHz of the spectrum in the 5.9GHz band [74].

DSRC is designed to provide high data transmission rates with a very low latency in the communication link. The new generation of DSRC overcomes the 915 MHz version with not only a higher data transmission rate, but also with communication range that can reach up to 1000 meters. Moreover, the 5.9 GHz DSRC has a lower interference probability that was reinforced with the spectrum allocation.

3.3 Applications

V2V and V2I communication and the DSRC enable the design of novel VANET-enabled ADAS applications [75]. This kind of communication makes it possible for any ADAS to use data collected by sensors located in other vehicles, thus considerably improving the sensing capabilities of individual vehicles [76, 77]. A high amount of research projects aim to address inter-vehicle communication issues. The feasibility of cooperative services using existent technology in the field of wireless mobile communication has been proved in several studies related to different kind of applications to support the driver like approaching crossroads and lane changing manoeuvres [78, 79]. Also most recent projects deal with the cooperative approach in the context of road transport safety through tests in real conditions [80] and V2V communication plays already a decisive role in several of these projects. V2I communications enabled by DSRC can already be found in commercial applications such as toll collection on highways or congestion charges in major cities. However, V2V communications are mostly driven by safety related applications. Examples of some of the proposed safety applications using V2V communications are the forward collision warning [81, 82] and the intersection collision warning [83].

3.4 Testbed

Most of this thesis work was done with the support from the DRIVE-IN project [84]. The project goal was to investigate how vehicular communication can improve the user experience and the overall efficiency of vehicle and road utilization. One of the main tasks of the DRIVE-IN project was the deployment of a real VANET using the RadiTáxis [85] fleet in the city of Porto. RadiTáxis with their 465 taxis are the largest fleet in the city. Currently 147 of these vehicles have DSRC radios installed. These are provided by Veniam [86], a spin off company that was created during this project. Moreover, they are equipped with an advanced taxi-dispatching developed by Geolink [87]. This taxi-dispatching system logs all the events, such position, taxi status, taxi stand identification or taxi stand's queue position.

These DSRC radios were used in our road experiments to provide the real-time V2V communication needed by our applications. Furthermore, the taxis logs were used to support the evaluation of an application presented in this thesis.

Chapter 4

Augmented Reality Driving: Safety

Road traffic injuries have become a global health and development problem of epidemic proportions. According to the World Health Organization (WHO) Global Burden of Disease Project for 2004 [7], road traffic crashes caused over 1.27 million deaths that year. In 2004, these crashes constituted the 9th leading cause of death and it was estimated that would rise to the 5th cause of death by 2030 [7]. If we account mortality in terms of years of life lost, then the significance of road crashes is even much more relevant as they are the first, second, and third leading cause of death of age groups 15-29, 5-14, and 30-44 years respectively [7].

4.1 The See-Through System

One of the most severe types of road crashes occurs when a vehicle shifts into an opposing traffic lane and crashes head-on with an oncoming vehicle. In the USA alone, there were 3,986 fatal head-on crashes in 2003, killing 5,063 people [88]. The Fatal Analysis Reporting System (FARS) indicates that the vast majority of these crashes occurs on rural, undivided, two-lane roads, and are the result of an inadvertent action of a driver, causing a run-off-road, or of a deliberate action, namely executing a passing manoeuvre [89].

The overtaking of long and vision-obstructing vehicles on the road, such as trucks, is a difficult and challenging task when there is no overtaking lane other than the one used by vehicles travelling in the opposite direction. Vision-obstructing vehicles, where the absence of transparent surfaces disables seeing through the vehicle, clearly reduce the awareness of drivers that travel behind such vehicles. As a result, a longer following distance is normally kept by the vehicle travelling behind, to improve the field of vision, as well as to increase the reaction time in the event of a sudden brake or manoeuvre by the vehicle in front. Additionally, the length of vision-obstructing vehicles is typically large. For example, the maximum overall length of a truck in the majority of the EU and European Economic

Area (EEA) member states is 18.75 meters. In some countries like Sweden and Finland this length can even reach 25.25 meters. In other areas of the world like Argentina, Australia, Mexico, United States and Canada even larger vehicles exist, called road trains that are used to move extremely large loads like several trailers. The maximal length of the largest road trains, which are the Triple and AB-Quad road trains can reach 53.5 meters.

Overtaking such vehicles through the use of the opposite direction traffic lane is thus a challenging task, and all the information that can support the decision of the driver in starting this manoeuvre is very useful. Drivers of such large and vision-obstructing vehicles are aware of such difficulty and we often observe their cooperation through hand-waving or actuation of turn signals to inform the driver behind that it is safe to overtake. VANETs allow replacing this unreliable driver-to-driver communication by automated V2V communication carried out through wireless technologies such as the Dedicated Short Range Communication (DSRC) protocol.

4.1.1 The See-Through System 1.0

Considering the difficulties inherent to the overtaking manoeuvre, we developed the STS. The STS is a cooperative ADAS for the overtaking manoeuvre of long and vision-obstructing vehicles that uses VANET technology to provide a video-streaming between the vehicle in front and the vehicle behind. The STS allows the overtaking vehicle to have the visual perspective of the road of the preceding vehicle, enhancing the driver's visual perception of vehicles travelling in the opposite direction lane. Figure 4.1 displays a snapshot of a possible road situation where STS is being used.

4.1.1.1 Architecture

An innovative system as the STS demands that in order to be prototyped and implemented we must follow some assumptions. The STS architecture assumes that:

- Equipped vehicles have windshield-installed cameras
- Equipped vehicles have high-precision GPS receivers
- Equipped vehicles have 802.11p DSRC radios
- Equipped vision-obstructing vehicles display a rear sign mentioning "STS Enabled" (a VANET enhancement over the typical "Long Vehicle" sign)
- Equipped overtaking vehicles have a screen on the dashboard can be visualized
- Equipped vehicles have an OBU

Figure 4.1: Road scenario showing the use of the STS

In the vision-obstructing vehicle, the OBU is responsible of gathering the raw video data from the windshield camera and compressing it. In suitable, two-lane roads, the traffic sign recognition software installed in the OBUs is able to detect if the overtaking manoeuvre is permitted by law. If some traffic sign does not allow overtaking, the activation of the STS will be automatically disabled. The "STS enabled" rear sign displays to the overtaking drivers that the vehicle in front of them is equipped with this cooperative system. Hence, drivers closely approach the rear of the vehicle to enable STS by pressing some context-aware button on the steering wheel. Since the overtaking vehicle also detects the "STS enabled" sign, the context for the button is automatically set by sign recognition. Upon the activation of the system, the overtaking vehicle sends a Geocast message to a Zone of Relevance (ZOR) determined through its current GPS position, direction vector and speed, asking for STS cooperation. The vehicle in front receives this message and validates its participation in the STS request based on its own current GPS position, direction vector and speed. Upon validation of its participation in the STS protocol, the vehicle in front starts a geo-unicast video streaming to the ZOR of the overtaking vehicle of the signal collected by its windshield-installed camera. The overtaking vehicle receives this video streaming and displays it to the driver through the dashboard screen. The overtaking vehicle sends a message to end the procedure when the overtaking is completed, which is automatically detected by its GPS position and the ZOR of the video-streaming.

An important aspect of the STS as an overtaking assistance system is that it just provides additional visibility, leaving the decision to engage in the manoeuvre to the driver of the overtaking vehicle. In terms of its function, the system is very similar to the rear-view mirrors that equip vehicles and that are also checked by drivers before engaging an overtaking manoeuvre. As happens with such rear-view mirrors, STS also suffers from blind-spots. Between the moment when opposite direction vehicles leave the area of sight of the camera of the vehicle that is streaming the video and the moment such vehicles enter the area of sight of the driver receiving the video, it is not possible to perceive them. It may seem that this blind-spot is very large, given the typical length of STS equipped vehicles, resulting in a dangerous assistance system. This is, however, a false perception, and the duration of such blind-spots is comparable to that of rear-view mirrors.

4.1.1.2 Implementation Foundations

The implementation of the STS is based on the current state of the art and evolving standards for automotive communication. Following the specifications and technologies proposed by European C2C-CC [90], the STS is an AU that uses the OBU of the vehicle to communicate.

As we highlighted in Section 3.1, vehicles periodically broadcast small data packets, known as beacons or heartbeats, to inform other vehicles in their communication range about their identification, current geographical position, speed and heading. Each vehicle also maintains a location table containing this information of every known vehicle, and such information is updated upon the reception of new heartbeats. Therefore, every vehicle equipped with the STS is aware of the other vehicles presence in the surrounding environment.

For safety reasons, an overtaking manoeuvre only makes sense when the vehicle in front is near and fully in the Line-of-sight (LOS) of the vehicle that intends to overtake. Thus, the involved vehicles must have direct communication, otherwise the AU of the vehicle that intends to overtake should not allow the activation of STS. If any kind of connectivity problem arises (i.e. network latency of video streaming) due to other vehicular safety messaging applications then the STS is deactivated automatically. Due to these natural conditions of overtaking manoeuvres, STS only requires single-hop communication, avoiding the overload of forwarding algorithms used in multi-hop communications. Therefore, upon the acceptance of STS cooperation, the vehicle in front initiates a video streaming session using single-hop broadcast. Once the wireless medium is shared, every vehicle within the communication range of the in front vehicle will receive the streaming packets, but only the vehicle that is interested in the STS cooperation will accept them.

4.1.1.3 Vehicle-to-Vehicle Video Streaming

Due to the nature of the STS and its safety issues, it requires a very low delay in the video streaming transmission. Since STS is only enabled when the involved vehicles have single-hop communication, applying video streaming between them does not face the challenges of a persistently partitioned network, and thus, complex architectures like the one described in [47] are not necessary for the STS requirements. Considering that the system has been conceived for situations where the vision of the driver is reduced by an obstructing vehicle ahead, and for typical two lane country roads and not for highways, a scenario with more than one or two cars activating the application at the same time does not apply. Even if, more than one car tries to activate the STS, the STS enabled vision obstruction vehicle uses the location table to analyse if the vehicle is right behind him and does not have another vehicle between them. Like a typical client-server application for the media transmission, the server side is responsible to stream its perspective of the road, and the client simply decodes and displays the stream that receives. In our implementation, the server extracts raw video data from the camera using the Video4Linux (V4L) library [91]. Before being transmitted, this raw data is encoded in order to deal with the delay and bandwidth constraints of the wireless medium. To encode the stream we initially used standard video codecs like MPEG-1 and similar codecs. However, these approaches make use of a frame buffer to correct possible errors with the transmitted frames, thus entailing problems related to delay on encoding/decoding the stream, which lead to unacceptable streaming delays, typically more than 1 second. To assure a real-time video streaming, we use Smoke Video codec [92], a low latency video codec. More specifically, the Smoke codec does not introduce delay regarding frame error correction/buffering. This codec is a plug-in of the Gstreamer Linux Framework [92].

The video-streaming packets must be carried in a typical RTP/UDP/IP real-time protocol stack. The Real Time Protocol (RTP) introduces timestamps that ensure timeliness of the packets. Packets that arrive beyond the delay threshold can simply be discarded without having to be processed by the higher layers. The packets are transported over UDP/IPv6 that simply is an unreliable connectionless protocol, which has a very small overhead and does not require establishing any prior connection.

4.1.1.4 Road Evaluation

The feasibility of the STS mostly depends on how the system would perform on the road. For the testing platform we establish a V2V wireless connection with a range of at least 300 meters. The 802.11p standard defines enhancements to 802.11 required to support Wireless Local Area Network (WLAN) in a vehicular environment. The DSRC/802.11p operates in the dedicated frequency band 5.9GHz, unlike the old DSRC systems that were designed for toll collection and operated at 915MHz band. The testing platform is constituted by the following elements:

- 2 LinkBirds MX V3 from NEC Electronics that provide DSRC connectivity
- 4 High gain antennas Mobile Mark ECOM6-5500 (5-6dBi) mounted on the vehicle roof
- 2 Laptops running Linux
- 1 Logitech Webcam located on the in front vehicle's windshield

We measure the system performance over the transmission process, in particular we focus on delay and packet loss as function of the distance. We used the Wireshark, a free and open-source package analyser [93] to log both sent and received packets of the preceding vehicle and overtaking vehicle respectively. Both computers had their internal clocks synchronized. Results show that the system assures a long-range connection with a very limited delay and a low packet loss. Given that the transmission path delay at $300m$ is around $1\mu s$, the only measurable delay is the system latency of the LinkBirds.

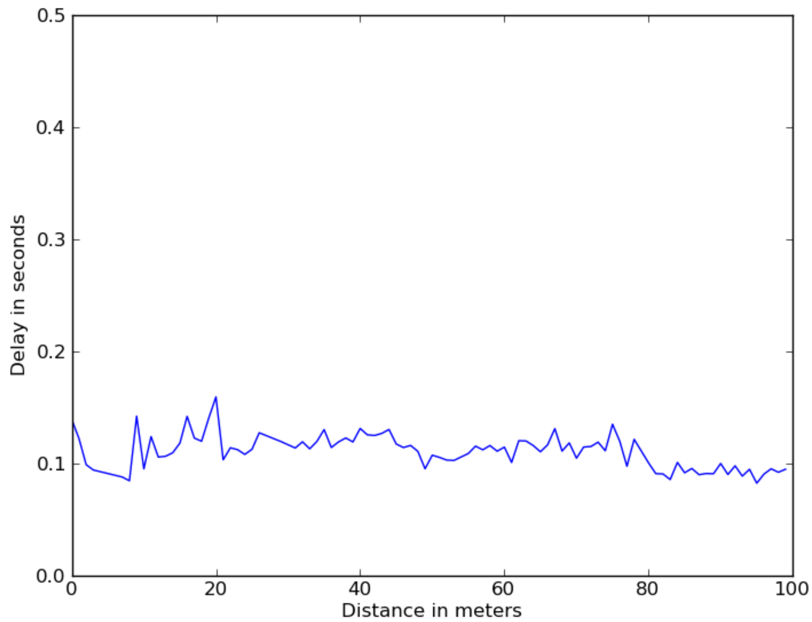

Figure 4.2: Delay measurements with the DSRC testing platform

Figure 4.2 shows that delay has no correlation to distance and it has a very high probability of being close to $100ms$. Figure 4.3 shows that packet loss is very low and it is not affected

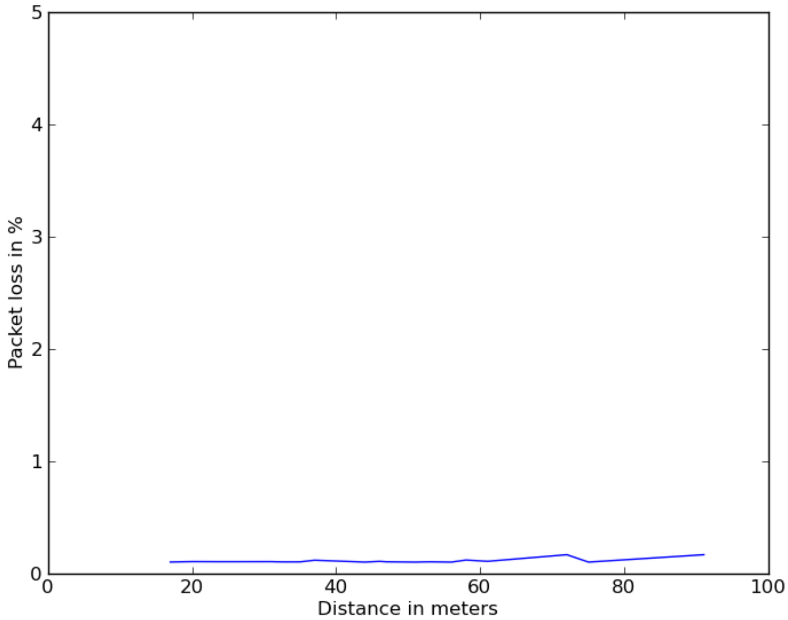

Figure 4.3: Packet loss measurements with the DSRC testing platform

by distance within the testing scenario limits. A mean packet loss close to 0.12% is perfectly negligible for wireless systems. Moreover, the bit resilience of streaming codecs can easily compensate this small packet loss. Note that preliminary tests showed that obtaining a real-time video streaming could be performed over RTP/UDP with the Smoke Video codec.

4.1.2 The See-Through System 2.0

In the previous section we presented the STS, which is able to transform large and vision-blocking vehicles into transparent objects that simplify the driver's task of evaluating the safety of a passing manoeuvre. This first version has safety issues regarding how the real-time video streaming that is received from the preceding vehicle is displayed on the overtaking vehicle. We first thought that displaying this image on a LCD placed on dashboard would be effective. However, the driver's glance time to evaluate the decision to pursue with the overtaking manoeuvre could result in accidents. Thus, the need to address these safety issues regarding the driver's distraction led to a new concept and approach for the STS.

We introduced an innovative concept where the new version of the STS relies on what we call the virtual windshield. This version, which we name the See-Through System 2.0, enables the virtualization of the windshield by using laser holographic projection [94] to display the received video-streaming directly in front of the eyes of the driver. We complement the V2V video streaming aiding the passing manoeuvre, that we originally presented in [15] with a more effective HMI. This HMI relies on computer vision, distance sensors and augmented reality to compute and display a partially transparent image that is super-imposed on the windshield to overlay the vision-obstructing vehicle. The novel interface provides a very intuitive message, essentially transforming the vision-obstructing vehicles in transparent tubular objects with the correct length. In particular, it conveys the critical notion of blind-spot, which is absent if we simply display the video streaming on a screen in the dashboard. This novel human-machine interface is a critical aspect of the this passing assistant, using augmented reality to simplify the reasoning of drivers on the interaction with the system.

4.1.2.1 Cooperative Communication Protocol

The STS 2.0 relies on an inter-vehicle communication protocol, in which the two vehicles involved in the system cooperate on the overtaking manoeuvre. Figure 4.4 presents a flowchart with the description of this communication protocol.

Periodic beacons sent by each vehicle enabled by the DSRC radios are part of the WAVE standard [14]. These beacons typically carry information with the location, heading and speed of the beaconing vehicle. In suitable areas for overtaking, which are detected by on-board road cartography or through the automatic recognition of road signs, the beacons can advertise that the vision obstructing (vehicle B in Fig. 4.4) is enabled with the STS cooperative system. This advertising can be activated by the detection of vehicles travelling behind, based on the same beacons.

If the vehicle intending to overtake (A in Fig. 4.4) receives the “STS enabled” beacons and is within a pre-defined distance of vehicle B (for example, 50 meters), then a “STS Available” sign is displayed to its driver. If the driver decides to activate the STS system, the cooperative protocol between the two vehicles is initiated, with vehicle A asking vehicle B for its relevant dimensions (length, height and width) and windshield camera parameters (mounting point and viewing angles). Vehicle B then sends this data to vehicle A, which computes the necessary frame resolution for the real-time video transmission, accounting as well with the distance to vehicle B.

In the STS 2.0, we implement the video streaming based on two levels of frame resolution which are associated with two distance intervals. The degradation of the wireless links performance as a function of the inter-vehicle distance is thus balanced through a reduction on the bandwidth requirements for streaming video with a resolution that reduces as the inter-vehicle distance increases. Vehicle A then asks vehicle B for the video streaming with one of those levels and updates the level of frame resolution request if the inter-vehicle distance changes to a different interval. During this stage of the STS 2.0 protocol, vehicle B

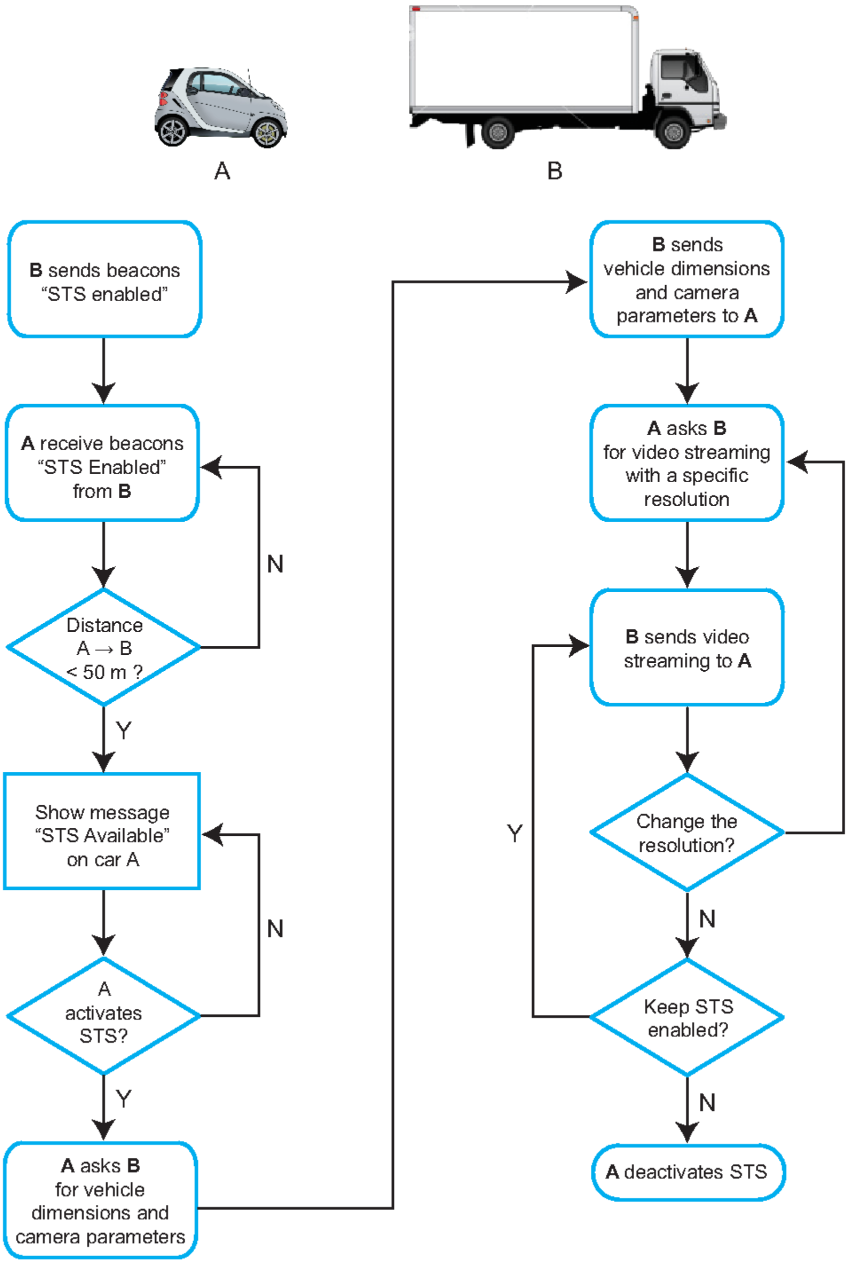

Figure 4.4: Flowchart describing the communication protocol between vehicles A and B.

just sends the video streaming with the required resolution.

The STS 2.0 protocol can be automatically terminated, based on the relative position and heading of the vehicles, or manually deactivated by the driver of vehicle A.

4.1.2.2 Augmented Reality Generation

As the vehicle intending to overtake receives the video-streaming from the preceding vehicle, it will have to generate a 3D-looking image that merges the video with a computed frame, representing the preceding vehicle as a transparent tubular object. This image has to be projected in a specific area of the windshield, overlaying the rear of preceding vehicle. We next describe how this image is computed.

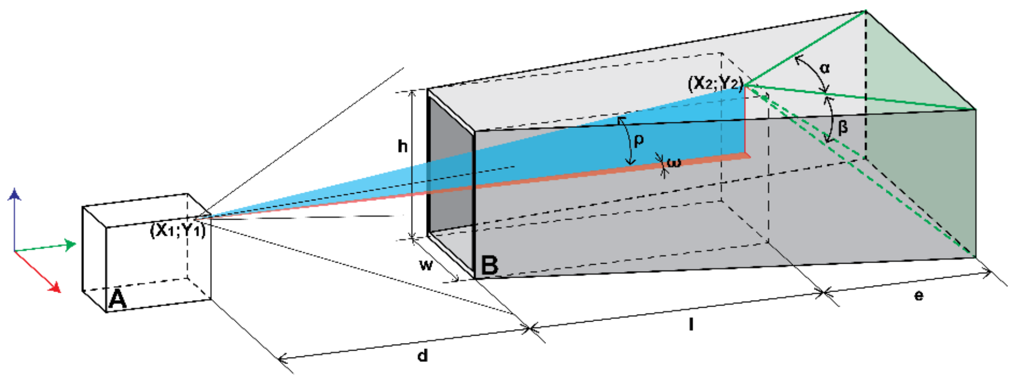

Figure 4.5: Scheme used in the augmented reality generation.

Figure 4.5 illustrates the scheme behind the generation of the 3D-looking image. The box A represents the vehicle that intends to pursue with the overtaking manoeuvre and the preceding vehicle is represented by the dashed box B. The non-dashed object displays the transparent tubular object with the shape that best conveys the visual perspective of the driver in vehicle A. Figure 4.5 displays several variables, such as inter-vehicle distance, inter-vehicle angles and preceding vehicle dimensions, that are used for the computation of the 3D-looking frame that will be super-imposed over the rear of the truck seen through the windshield. The description of these variables can be found in the Table 4.1.

The 3D-looking image grounds on two elements: the video-streaming and the shape of the transparent tubular object. The angles α and β allow us to compute the distance at which the camera can see the road, e. Adding the computed e and the length of vehicle B, l, we can generate a tubular object with a more realistic length that reflects a more accurate distance at which the objects are captured by the camera. We can thus provide the driver with a better depth perception of the video-streaming transmitted by vehicle B. Furthermore, the image conveyed to the driver needs not only to give a real depth perception of the real distance of the objects in the video-streaming, but also to exhibit possible limitations that can arise from this system, such as the blind-spot. This limitation emerges as a consequence of the fact that the video-streaming only displays the view beyond the distance at which the

Variable	Description
(x_1, y_1)	position of the driver's eye point
(x_2, y_2)	position of the camera
d	distance between vehicles
e	distance from camera to the ground capturing point
h	height of the vehicle B
l	length of the vehicle B
w	width of the vehicle B
α	horizontal view angle of the camera
β	vertical view angle of the camera
ω	horizontal angle between (x_1, y_1) and (x_2, y_2)
ρ	vertical angle between (x_1, y_1) and (x_2, y_2)

Table 4.1: Description of the variables used for framing the video

camera starts to capture the road.

Figure 4.6 shows the schematics of the computed image representing the 3D-looking frame on which the video-streaming is super-imposed, where we can observe two distinct panels. First, the outside frame that overlays the rear of the preceding vehicle. Second, the inside frame which reproduces the front view of the tubular object, by rendering the video-streaming. This image needs to be placed on the windshield in a way that overlays the rear of the preceding vehicle. Computer-vision algorithms allow us to define this windshield area, making possible to outline the outside frame. However, to properly overlay the image, it needs to be shifted considering the relative position between the driver's eye point and the center of the windshield. This is similar to the calibration of rear-view mirrors, and could be setup accordingly.

The key to compute the image grounds on the ratio r between the computed width/height of the area (w_0, h_0), and the real width/height of the preceding vehicle (w, h). As the proportions of the image's dimensions are still the same, we can use either (h_0, h) or (w_0, w) respectively to calculate the ratio. In Equation 4.1 we use the (h_0, h). This ratio will continuously reflect the current distance, not only to the rear of the preceding vehicle (d), but also to the ground capturing point of the windshield camera $(d + l + e)$. Equations 4.2 and 4.3 reflect the constant re-computation of the outside frame (w_o, h_o) and the equations 4.4 and 4.5 the inside frame (w_i, h_i). Moreover, this image changes according to the relative position between the driver and the camera, given by the angles ω and ρ. This will not affect the size of both frames, it just shifts the inside frame horizontally (ω) or vertically (ρ). However, if these angles are too wide, the inside frame needs to be cropped in order to

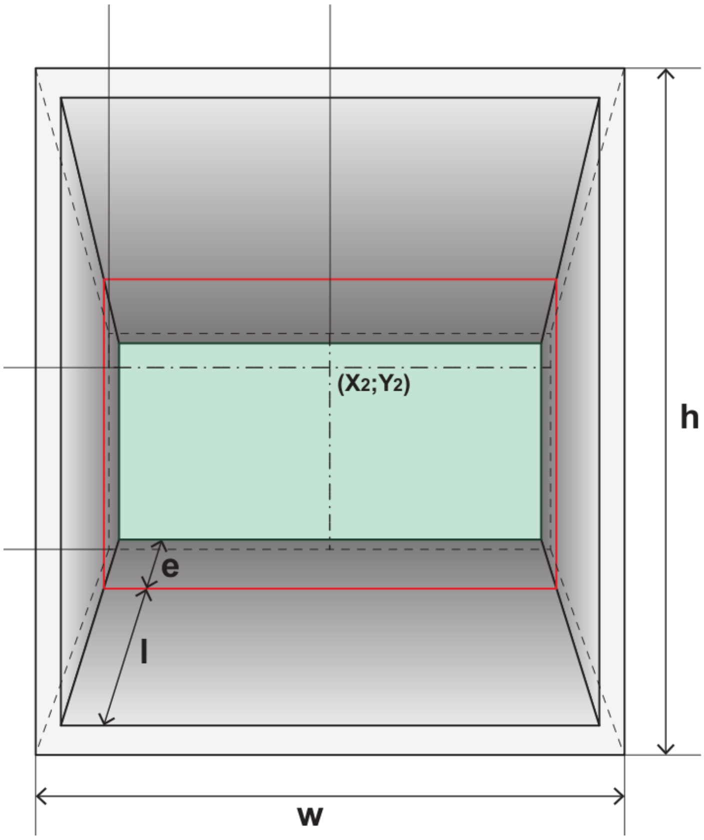

Figure 4.6: Schematics of the computed image representing the 3D-looking frame on which the video-streaming is super-imposed.

fit the outside frame. Finally, we link the correspondent vertex of each frame, resulting in a 3D-looking image that displays the video-streaming of the preceding vehicle with a realistic depth perception.

$$r = \frac{\frac{h}{h_0}}{d_0} \tag{4.1}$$

$$h_o = \frac{h}{d * r} \tag{4.2}$$

$$w_o = \frac{w}{d * r} \tag{4.3}$$

$$h_i = \frac{h_0}{(d + l + e) * r} \tag{4.4}$$

$$w_i = \frac{w_0}{(d + l + e) * r} \tag{4.5}$$

To be more accurate, we can use a system that uses the camera placed in the windshield to compute the distance between vehicles [60]. It focuses on the point of the contact of the vehicle and the road, which combined with the horizontal field of view and the height at which the camera is. Therefore the computation can be performed with a relative smaller percentage error.

4.1.2.3 Network Performance

We measured the performance of the overtaking assistant showing whether and how the packet delay values for a given set of road-based experiments change over the transmission process using both DSRC/802.11p and 3G technology. 3G is becoming a common technology to enable connected vehicles and it is thus important to evaluated the feasibility of our passing assistant based on this communication technology. We have thus performed several field tests using two experimental vehicles on the road.

Our first evaluation uses a one-hop ad-hoc approach with the DSRC/802.11p, in which both vehicles communicate directly. Our second evaluation uses an infrastructure-based approach using 3G technology. These evaluation tests were performed in a countryside scenario where this type of assistant is more useful and can prevent head-on collisions.

The 802.11p standard defines enhancements to 802.11 required to support WLAN in a vehicular environment and it operates in the frequency band of 5.9 Ghz. The testing platform is constituted by the following elements:

- 2 LinkBirds MX V3 from NEC Electronics that provide DSRC connectivity;
- 4 High gain antennas Mobile Mark ECOM6-5500 (5-6dBi) mounted on the vehicle roof;
- Enhanced wireless drivers for establishing connectivity between vehicles;
- 1 Logitech Webcam located on the windshield.
- 2 Laptops running Ubuntu Linux.

The results in the Fig. 4.7 show that during the transmission process, the 802.11p had a stable behaviour in terms of packet delay. This behaviour, coupled with its low packet delay, enables the support for real-time video streaming over VANET. With DSRC, the driver sees the image with approximately $100ms$ of delay. This value is practically unperceptive to the driver, and thus enables the safe usage of this cooperative assistant to help in the decision to engage in an overtaking manoeuvre.

Cellular-based connectivity in vehicles is becoming very common, supporting real-time traffic information systems, remote diagnostics or emergency-related messages. Considering this reality we decided to evaluated the feasibility of our passing assistant using 3G networking,

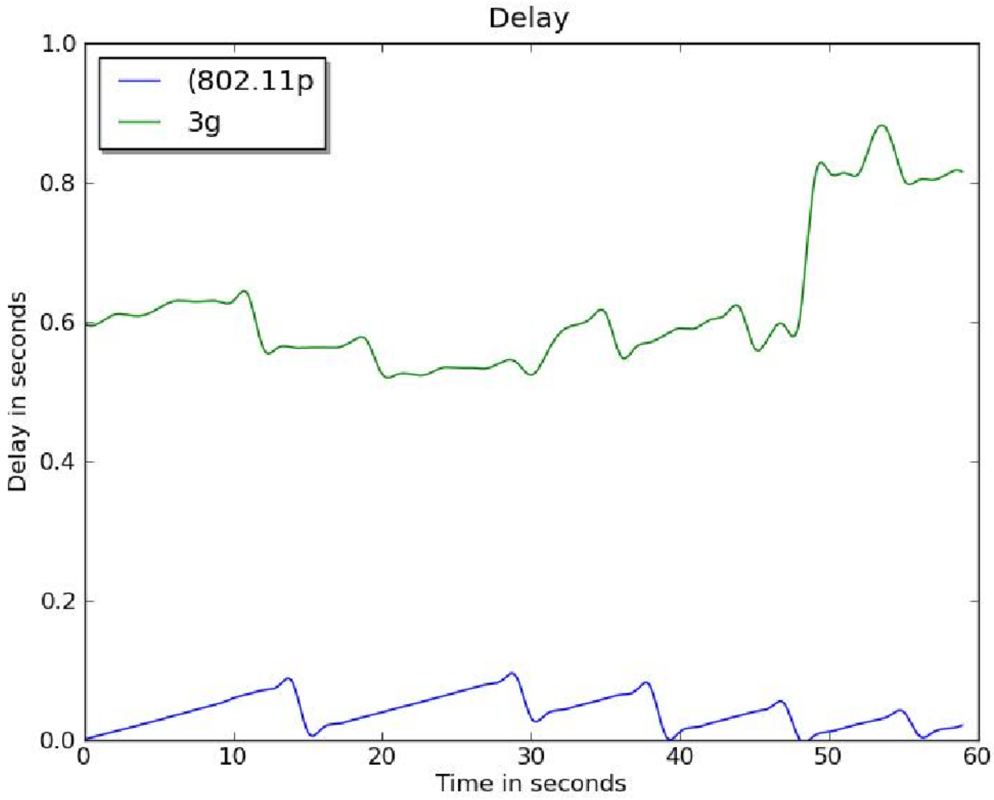

Figure 4.7: Packet delay observed during one minute of a road experiment, with DSRC and 3G

evaluating the associated packet delay. We have not evaluated with Long Term Evolution (LTE)/4G technology due to its unavailability in Portugal at the time of the evaluation.

The testing platform is constituted by the following elements:

- 2 3G Network Adapters
- 1 Logitech Webcam located on the windshield.
- 2 Laptops running Ubuntu 10.10 system.

As we can see in the Fig. 4.7 the results using the 3G cellular infrastructure, which report a delay higher than half a second, are not compatible with the requirements for an overtaking assistant. This type of delay would translate into a gap of tens of meters between the real position of incoming vehicles and the position perceived through the video-streaming.

While 3G can enable several applications relying on connected vehicles, it cannot support the low-latency video streaming required for the passing assistant. DSRC, on the other hand, is able to provide the necessary communication latency and is also, based on its ad-hoc nature, compatible with bandwidth constraints that could also arise from the use of 3G networking. In Fig. 4.8 we can see the difference between the location of an oncoming vehicle with zero, 100ms delay, and 500ms delay transmission.

Figure 4.8: Comparison of the video streaming without delay, frame a), with 100ms delay, frame b), and with 500ms delay, frame c).

4.1.3 The See-Through System - Prototype

The concept of the virtual windshield was introduced with the previously described STS 2.0. We conceptualized the use of the laser holographic projection on the windshield to overlap the driver's perspective of the rear of the preceding vehicle. Prototyping the STS using such technology is still inconceivable at this time. Recently, the display industry has made some advances with transparent LCD which completely fit our virtual windshield concept, thus perfect for implementing the STS. We used a transparent LCD made by Samsung [95] in the prototype of the STS.

4.1.3.1 Architecture

With the natural evolution of the STS, the system architecture has suffered from some improvements and minor changes. The system design was driven by safety requirements, due to real-time nature of the STS for providing a cooperative video-based ADAS, The STS is comprised of three main subsystems: the unidirectional video-streaming chain, the bi-directional control module, and the computer vision and human-machine interfaces. The Figure 4.9 shows the improved architecture of the STS.

- **Unidirectional video-streaming:** As previously mentioned, the video-streaming chain was designed to provide low latency video streaming based on DSRC communications. Therefore, we employ the Smoke video codec that is a low latency video codec provided by the GStreamer Linux framework [92]. The video-streaming packets must

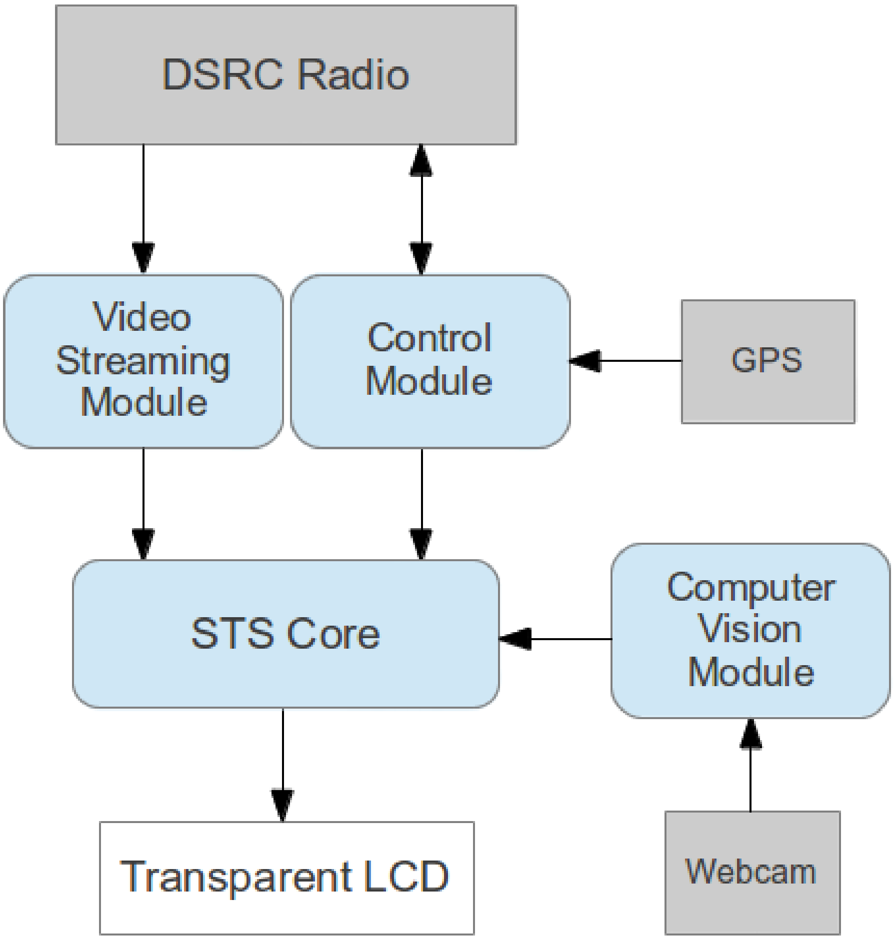

Figure 4.9: See-Through System architecture.

be carried in a typical RTP/UDP/IP real-time protocol stack. The RTP introduces timestamps that ensure timeliness of the packets. Packets that arrive beyond the delay threshold can simply be discarded without having to be processed by the higher layers. The packets are transported over UDP/IPv6 that simply is an unreliable connectionless protocol, which has a very low overhead and does not require establishing any prior connection. The DSRC radios are equipped with a single antenna WAVE/802.11p and implement the IPv6/802.11p dual-protocol stack. The latter carries the video-streaming over one of the several 802.11p 10MHz service channels.

- **Bi-directional control module:** This subsystem provides the cooperative capabilities of this ADAS system, since it is responsible for establishing the connection, monitoring the operations and assuring the safety of the takeover manoeuvre. The control module receives the different inputs from the vehicle sensors, the geographical and car awareness from the DSRC radio and the visual awareness from the windshield camera. After determining that all safety requirements are met, it initiates a connection with the vehicle in front and negotiates the establishment of the video-streaming connection. The vehicle in front transmits static information on the vehicle characteristics, e.g. vehicle dimensions, and information on the vehicle dynamics, e.g., speed, braking, acceleration. It also monitors the reliability and the timestamps of the received packets and disengages the system if the safety requirements are not met.

- **Computer vision and human-machine interfaces:** These interfaces are constituted by the following elements: front-facing windshield camera; transparent LCD monitor; dashboard interfaces. The camera has two roles: provide road signs detection; visually detect the edges of the preceding vehicle. The computer vision module process the visual information and uses the vehicle dimensions information provided by the control module to match these to the image obtained with the camera in order to detect the vehicle edges. Furthermore, this module cue the control module relative to the detected road signs, such as speed limits or overtaking forbidden signs. It also calculates the 3D-looking frame that provides the depth perception that matches the perspective of the driver with the camera of the vehicle in front. The transparent LCD monitor is mounted on the windshield, allowing the video streaming image to be correctly superimposed on the field-of-view of the driver, as well as the visual bracketing information of incoming vehicles. Finally, the dashboard interfaces allow the driver to activate the STS, which could be a dedicated or multi-function button on the steering wheel. Alternatively, it could also be activated with a set of conditions, including the activation of turn signal lights.

4.1.3.2 Hardware

The hardware used in the implementation and prototyping of the STS comprises:

- 2 Vehicles
- 2 Laptops running Ubuntu Linux
- 2 GPS receivers
- 2 802.11p DSRC radios
- 2 High-gain antennas Mobile Mark ECOM6-5500 (5-6dBi)
- 2 High-resolution Logitech C270 webcams
- 1 Samsung Transparent LCD

Each vehicle is equipped with a laptop running Ubuntu Linux 12.04, a high-resolution webcam, a GPS receiver and a DSRC radio equipped with a high gain antenna. We used 802.11p compliant radios based on the Unex DCMA-86P2 chip [96]. These radios implement the WAVE standard [14]. The overtaking vehicle is also equipped with a transparent LCD to provide the augmented reality apparatus needed by the STS.

For the STS purposes, the preceding vehicle must be a truck or an equivalent vision-obstruction vehicle. A magnetic coloured board is attached to the rear of this vehicle, in order to its detection by the overtaking vehicle can be fast and accurate.

4.1.3.3 Software

The software implementation of the STS is designed to deliver the user with a reliable and intuitive system. Due to the nature of this system and its criticalness, we chose C++ as the main programming language. Its low memory usage, speed and the possibility to integrate with all type of frameworks, were the main choice factors. As previously mentioned, the GStreamer framework [92] was used to provide the real-time video streaming pipeline between the two vehicles. More specifically, we used its C++ and OpenGL plugins that make it possible to directly integrate with the rest of the software.

- **Computer Vision:** It allows to correctly super-impose the video-streaming that comes from the preceding vehicle over its rear. We used the Open Source Computer Vision Library (OpenCV) [97], which provides all the functions needed to perform the vehicle detection, and aims to real-time detection. In order to simplify the detection algorithms, we installed a uniform colour magnetic board in the vehicle in front.

  Generally, the detection is done in two steps. First, we perform the color segmentation based on a predefined color range. Figure 4.10 displays the result of applying this technique to the frame captured by the webcam placed on the windshield of the overtaking vehicle. The white area represents the coloured areas that are within the predefined color range. Second, we detect the contours that the resulted image has, and we test if those contours match a rectangle. If a match is found, those contours are used as bounds of the 3D-looking image with the video-streaming embedded.

- **Frame Generation:** The frame generation of a 3D-looking image that merges the video with a computed frame occurs immediately after the in front vehicle has been detected. This image is then displayed on a transparent LCD placed on the windshield. The description of how this frame is generated can be seen in the Section 4.1.2.2.

Figure 4.10: Image representing the color segmentation technique applied.

4.1.3.4 Experimentation and Validation

In order to be solid and trustworthy, this implementation of the STS needs to be tested both on the road and in a real scenario. In this section, we describe this road experiment, more specifically where and how it was performed. Furthermore, we define our validation methodology and present the results that we obtained.

Experimentation Setup

As the STS is focused on providing a real-time video-based cooperative-ADAS that could cause life-threatening situations, we chose to held it in a closed road to ensure safety while performing the experiment. This road was similar to the country roads for which this system is primarily designed to.

For creating the scenarios that make possible to validate this system, several vehicles were used to simulate the normal traffic that we can find in a normal situation in this type of roads. During the experiment, the distance between the overtaking and preceding vehicles was kept within a 50 meters range. Considering the link quality between the DSRC radios, the video resolution was adjusted to ensure that all the video frames were displayed in the overtaking vehicle. All the experimentation setup parameters are described in Table 4.2.

Table 4.2: Experimentation Setup Parameters

Scenario Setup	
Road Topology	Two-way road
Lanes	Single Lane
Road Scenario	Country road
Distance between vehicles	$\leq$ 50 meters
Legal speed limit	90 Km/h
Preceding Vehicle	
Model	Volkswagen Transporter T5
Length	529 cm
Width	190 cm
Height	199 cm
Streaming	
Video Codec	smoke
Video Resolution	640x480/340x240
Frames per second	30
Application	
Frame Display Frequency	30 Hz
Vehicle Detection Frequency	20 Hz
Position Update Frequency	1 Hz

Validation Methodology

This experimentation setup was designed not only to demonstrate the implementation of the STS but also to validate it as an efficient and reliable system. Therefore, the validation methodology focuses on achieving two goals: show that the Quality-of-Experience (QOE) of the video-streaming meets the safety requirements in terms of end-to-end delay and image quality as perceived by the driver; show that the blind spot visual representation corresponds to its physical characteristics.

For the first goal, we analysed the different contributions to the end-to-end delay. Furthermore, we inserted visual timestamps into the video-stream and compared them in a split screen image. We also analysed the video capture delay by recording the image of the timestamp clock and comparing it with the raw stream obtained from the camera. With this methodology, we also extended it to analyse the encoding and decoding delay of the codec, by providing a local playback of the encoded stream.

For the second goal, we analysed a static and a dynamic scenario. In the static scenario, we positioned the vehicles on the road segment and took different photographs and screen captures in order to guarantee that the blind spot representation is accurate. In the dynamic scenario, we used an incoming vehicle to pass at different speeds, while recording the received video-stream as well as a video capture from the point of view of the driver. The absolute speed of the incoming vehicle must be high in order to obtain a realistic relative speed of traffic travelling in opposite road lanes.

Finally, we tested the system as operating in a normal road scenario and obtained the different analytical measurements as well as personal experience from using this system while driving.

4.1.3.5 Expected Results

The expected results in terms of delay depend on the individual delay contributions associated to the application and network layers.

- **Application layer delay:** The STS consists of several modules in which each one introduces a delay that tends to be constant. This was considered during the implementation phase. Nevertheless, both hardware and software where the STS runs will also affect the application layer delay. The frame capture delay depends on the webcam used, on the capacity of the operating system to process the raw data that comes from the device, and the performance of the library used. This delay tends to overcome the frame display delay, which depends on the frame rate of both application and display. Furthermore, the vehicle detection introduces a negligible delay and the application was designed to perform the detection in parallel with the frame display. Considering the overall delay, the application layer delay will be substantial, though this can be easily improved in the future with the hardware and software evolution.

- **Network delay:** The WAVE/802.11p protocol stack includes the Enhanced Distributed Channel Access (EDCA) that provides a probabilistic mechanism for traffic prioritization in terms of channel access. This allows for the transmission of high-priority traffic such as real-time video-streaming in the presence of low-priority traffic. The stack also defines a Service Channel (SCH) and a Control Channel (CCH), where the latter must be monitored by all devices for exchanging safety-related data. In order to support single radio DSRC devices, it is mandatory to support channel switching between CCH and SCH, with synchronization provided by the Coordinated Universal Time (UTC) clock from the GPS signal. Therefore, the network delay will be mostly due to channel switching, usually defined in $50ms$ time-slots, which bounds the channel access delay to 50-$60ms$, when considering all the guard times and different transmission rates. However, this assumes that all the packet queueing and scheduling mechanisms are properly implemented and that there are no other high-priority data transmissions.

4.1.3.6 Obtained Results

During the experimentation, the 802.11p radio devices provided a low-delay and stable transmission. The results in the Figure 4.11 show that we obtained a network delay of an average of $65ms$ during the STS activation range, 50 meters. The overall delay of the STS also comprises the application layer delay. The process of capturing a single video frame from the webcam, encoding, decoding and display such frame takes approximately $100ms$. Adding the frame display frequency (see Table 4.2), the delay increases to $133ms$. As we expected, the delay of the application layer was significant. Combining both network and application delays we have a delay near to $200ms$. Nevertheless, in the worst scenario with a combined velocity of 180Km/h, which reflects both overtaking and oncoming vehicle travelling at 90Km/h (legal speed limit in country roads in Portugal), the overall delay will create a visual gap of 10 meters, which for the STS is almost negligible.

4.1.3.7 Implementation

The final result of the STS implementation is shown in the Figure 4.12. This image illustrates the process of super-imposing the video streaming that is transmitted by the preceding vehicle on its rear. We can observe the video streaming embedded in the frame generated using the method described in Section 4.1.2.2. The transparent LCD provided the best

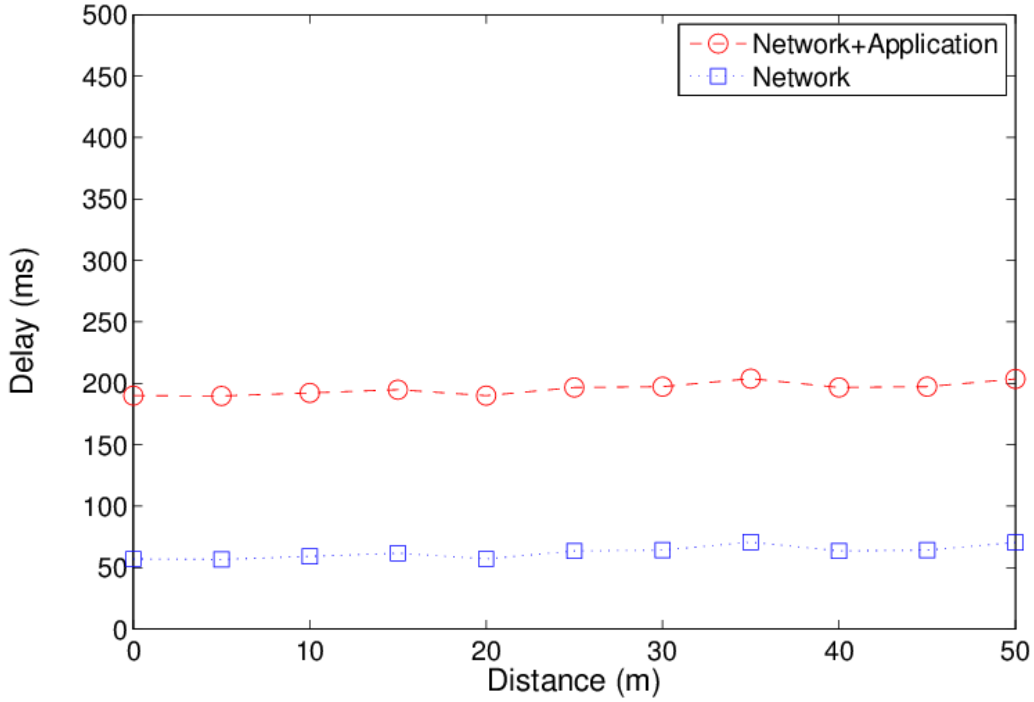

Figure 4.11: Delay versus distance.

apparatus for implementing the STS. However, due to this LCD being a prototype, it lacks the ability to completely block the background, which results in a magenta tinted image as a result of the coloured panel attached to the rear of the preceding vehicle. Thus, the coloured background that appears on the image in the Fig. 4.12.

Figure 4.12: STS being activated in a country road scenario. The generated frame, containing the video-streaming, super-imposes the rear of the preceding vehicle.

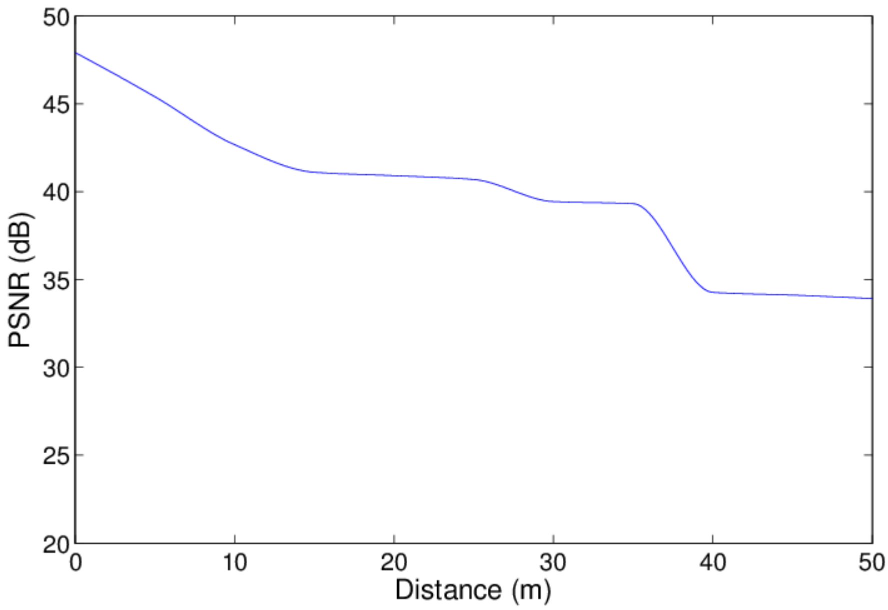

Figure 4.13: PSNR versus distance.

The STS demands that the video streaming is real-time and that its quality provides the driver a perfect representation of what the preceding vehicle sees. The smoke codec of the Gstreamer framework allowed us to transmit in real-time without almost any delay. We analysed the quality of the frames received in the overtaking vehicle to ensure that the video streaming is up to the demands of this system. The Peak Signal-to-Noise Ratio (PSNR) is a simple analytical method for measuring the video quality, which provides a basic understanding of the QOE especially when the main focus is on measuring the quality in a wireless environment. Figure 4.13 shows the computed PSNR values between the captured and displayed video sequences. During the first 40 meters, these video sequences were almost undistinguishable (PSNR greater than 36 dB). And, between 40 and 50 meters the PSNR was above 30 dB, which corresponds to acceptable visual quality.

Another issue addressed in the STS implementation was the evaluation of the blind spot that this system presents. These blind spots are specially significant for long vehicles. Due to logistics, we were not able to perform the experimentation with such long vehicles on this first implementation. Hence, it was used a Volkswagen Transporter T5, which is a much smaller vision-obstruction equivalent.

We created a scenario with a vision-obstruction vehicle, an overtaking vehicle and an on-coming vehicle on the opposite lane. The objective was to observe and detect the possibility of a blind spot in the STS. Considering that the blind spot occurs mostly when the distance between vehicles is reduced, the overtaking vehicle was placed a few meters behind the preceding vehicle. In the Figure 4.14, we can depict a small blind spot, where the oncoming vehicle does not appear on the video streaming, and we can only see part of it. This blind spot would be more significant, if a longer vehicle was used as the preceding vehicle. With such vehicle, for instance a semi-trailer truck, we would not be able to see the oncoming vehicle both on the video streaming and the point of view of the driver.

Figure 4.14: Blindspot generated by the STS.

4.1.4 The See-Through System - AR Glasses

In our first prototype of the STS, we used a transparent LCD installed on the windshield as the Human Computer Interaction (HCI) architecture that provides the optical AR needed to implement the STS. We observed some problems using the transparent LCD technology installed on the windshield. First, the optical transparency of the LCD that we used was not ideal and caused some blurred vision of the non-digital content. In addition, the fixed position of the LCD in relation to the point of view of the driver also resulted in misalignment in some situations in the super-imposition of the digital content and the real-world object, which can be observed in [1]. Eye-tracking system could mitigate this problem.

To overcome these problems, we implemented the STS' HCI using AR smart-glasses. We believe that in a near future AR-enabled cars could contain factory-installed integrated smart glasses, which would be connected to other sensors of the car and be used by drivers as naturally as sun glasses or safety belts.

4.1.4.1 Implementation

Comparing to the previous implementation of the STS, we used the Vuzix® STAR 1200 XL smart glasses [98]. These glasses feature a 1080p camera, adjustable eye-separation and 35-degree diagonal field-of-view. The Vuzix® glasses' transparent widescreen video displays provide a see-through perspective even when we overlay 2D or 3D content, which is perfect for the STS. As specified by the STS, its implementation requires a vision-obstructing bus or truck as the preceding vehicle and a passenger car as the overtaking vehicle. Naturally, both vehicles must be equipped with DSRC radios and GPS receivers. The preceding vehicle is equipped with a high-resolution camera on its windshield and the overtaking vehicle's driver uses the Vuzix® glasses. Similarly to the previous implementation of the STS, we used laptops connected to all the devices in each vehicle to run the experiment. The DSRC radios provide the low-latency video-streaming with the perspective of the preceding vehicle. The distance between vehicles used in the frame generation is provided by the GPS receivers placed in both vehicles.

This HCI implementation overcomes the issue with the driver's perspective display calibration exhibited in the previous implementation using a transparent LCD to display the STS. Comparing to the transparent LCD, the blurred vision of non-digital content is also totally non-existent using the Vuzix® equipment. Figure 4.15 shows the usage of the Vuzix® glasses in our test-drive experiments.

These glasses have an embedded camera on the bridge of the nose that records the exact perspective of the driver's eyes. Furthermore, the glasses' displays are placed right in front of the eyes, thus producing a more accurate AR immersion. Using the embedded camera and computer vision we are able to detect the rear of the preceding vehicle in such a way that we can overlap the 3D-looking frame with the embedded video-streaming. The STS implementation using the Vuzix® glasses can be seen in Fig. 4.16. In this figure we are able to observe the seamless blend of digital objects with the real-world content, where the STS's 3D-looking frame is almost undistinguishable from the real objects. In frame a) we show the driver's perspective with STS disabled. In frame b) we show the AR result with STS enabled. Note that the snapshot shown in frame b) results from an offline photo-montage that merges a video recorded using the glasses (without AR) with the AR content (3D boundary frame and video) that is actually sent to the glasses display. It is impossible to obtain an actual snapshot of the driver's vision while using the glasses.

Another important issue of the implementation of STS with smart glasses compared to the transparent LCD implementation, is that the complex setup of the transparent LCD

Figure 4.15: Vuzix® STAR 1200XL AR glasses used in the vehicular environment.

solution, together with the legal issues involving windshield-installed systems in public driving scenarios, forced for a test-drive in a closed area with this solution, while using the smart glasses we were able to make the driving experiments in common and public driving scenarios.

4.1.5 The See-Through System on the Media

The STS is probably one of the most innovative and relevant V2V applications presented and prototyped so far. Due to the impact that we observed when presenting it in international conferences, we concluded that creating a professional video with the implementation of the STS would be crucial for promoting the system on the media. Therefore, together

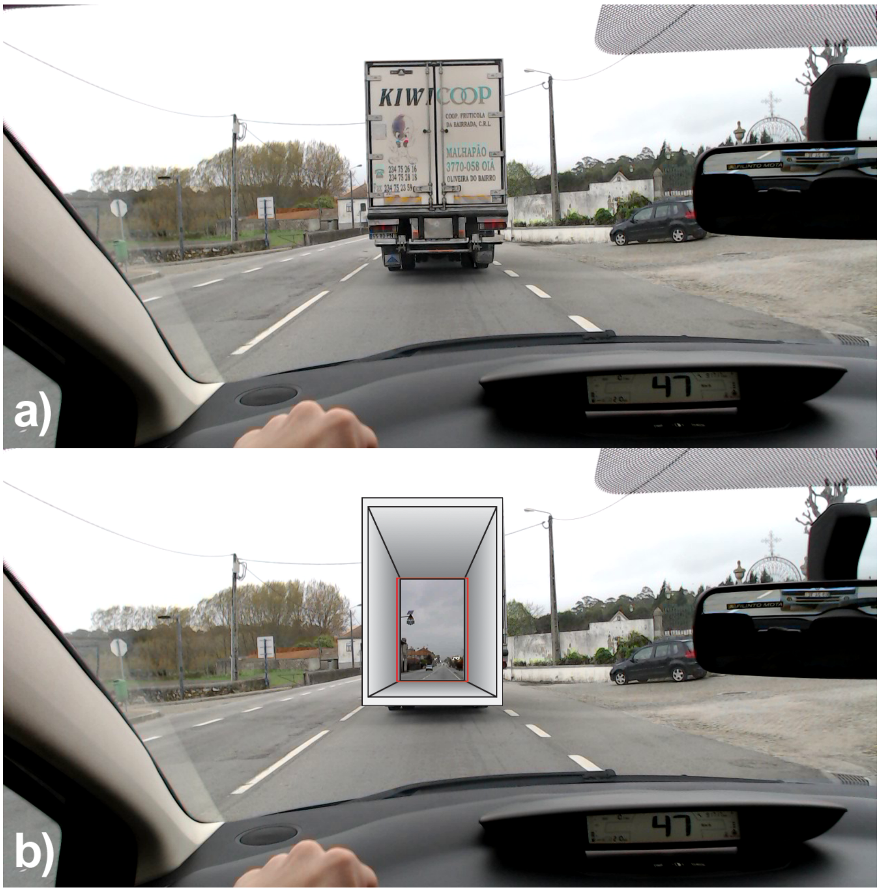

Figure 4.16: See-Through System implemented using Vuzix® STAR 1200XL AR glasses.

with the Portuguese audiovisual production company Cimbalino Filmes [99], we produced a promotional video that presents the STS and shows its implementation using the transparent LCD [1].

This video shows a prototype of the STS using the transparent LCD as HCI that delivers the system to the driver that intends to overtake. We used a long and vision-obstruction vehicle, namely a bus, as the preceding vehicle. Furthermore, we used two light vehicles: one for the overtaking vehicle; and one for the oncoming vehicle. This experiment was performed in a country road, specifically the type of the road for which this system was designed for. Figure 4.17 shows the apparatus of the experiment. The frame on top shows the country scenario where we performed this experiment. While the frame on bottom shows the STS being activated using the transparent LCD as the HCI.

Figure 4.17: Snapshots of the promotional video of implementation of the STS using a transparent LCD.

4.1.5.1 Impact on the Media

Since the presentation of the STS in 2010, this system has been praised as the perfect example of a V2V application by the scientific community, and has always being well received. The last iteration of the STS which focused on using the Vuzix®AR glasses as the HCI, gained attention from the media. The worldwide known scientific magazine NewScientist highlighted the system in an article [100] as an useful application to be introduced in future vehicles. Afterwards, the worldwide media advertised the system as an innovation that can lead to a significant reduction on deaths caused by head-on collisions. Known and respected magazines and news sources, such as Smithsonian Magazine [101] and Spiegel [102] also wrote articles about the STS. Furthermore, Portuguese television channels RTP, SIC and Porto Canal made reports about the STS. More than 220 different news sources, blogs, automotive, scientific, or technology websites highlighted the STS in their articles. A compilation of these sources can be seen in [103].

4.1.5.2 Video Analytics

With the impact of the STS on the worldwide media, the audience of the promotional video increased both on the number of visualizations and localization. By December 30th 2013, the number of visualizations was approximately 158,000. This is an impressive number considering the type of video (scientific video) and the lack of paid promotion of this video. These visualizations spread across the world and the video was seen at least one time by 178 countries totalling 91% of the 196 countries in the world [104]. Figure 4.18 depicts this impact throughout the world.

Together, Russia and United States of America captured nearly one third of views of the promotional video. The top 10 locations by number of views is:

1. Russia
2. United States of America
3. Vietnam
4. Spain
5. South Korea
6. Ukraine
7. Brazil
8. Netherlands
9. Hungary
10. Slovenia

Figure 4.19 illustrates the video's demographics. We can highlight that the majority views were made by adults that can drive (18-65+ years) representing 86.9% of the views. However, regarding the gender, there is a huge difference between male (89.5%) and female (10.5%).

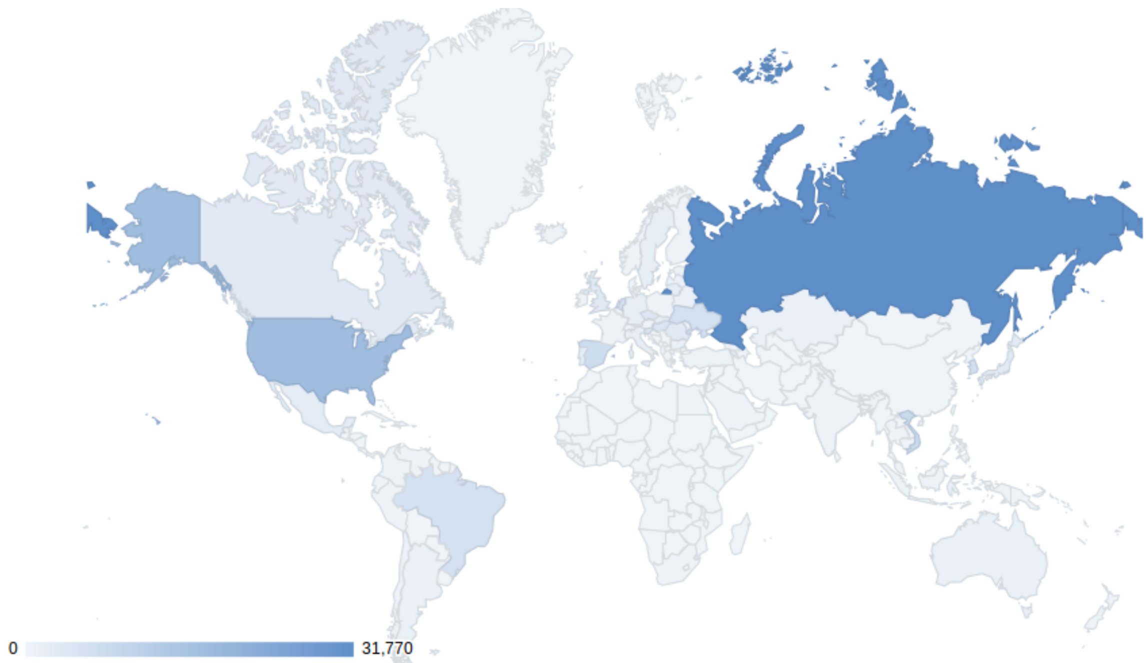

Figure 4.18: Number of views of the promotional video [1] by country (December 30th, 2013).

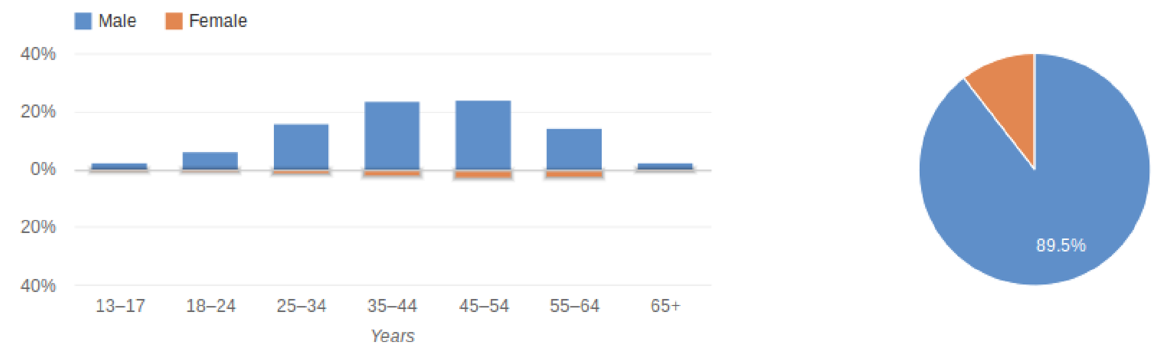

Figure 4.19: Promotional video's demographics (December 30th, 2013).

4.1.5.3 Conclusions

Based on the presented numbers, we can conclude that the STS was accepted by the general media and population throughout the world. Hence, we can conclude that the STS is an useful ADAS that can be introduced in future vehicles. As a result of this impact, we were invited to publish on the Global Village online magazine. We were also contacted by a leading automotive manufacturer with strong presence in the market of passenger vehicles as well as trucks and buses. This contact is still at an early stage, but with clear intentions of developing collaborative work in the near future.

4.2 Multi-vehicle Cooperative Systems

With VANETs, vehicles can relay relevant information to their neighbours, thus enabling different types of cooperative systems. Vehicles can cooperatively forward safety information to avoid dangerous situations such as multi-vehicle collisions or low-visibility related collisions. Innovative cooperative-ADAS can use such information and display it using both visual and/or audible AR. In this section we describe two different multi-vehicle cooperative systems each one using respectively audible and visual AR.

4.2.1 Virtual Surround Sound

Driving is a multi-sensory experience and it is reasonable to state that it mainly relies on vision for regular tasks and audio for alerts. Sirens have been in use since the 1920's and horns date back to the first horseless carriages that were introduced long before motor vehicles. From a human reaction point-of-view, audible stimuli [105] produces a much faster reaction time than visual stimuli. Furthermore, most people are able to perceive the directionality of the sound. Some ADAS for parking assistance are only based on audio cues and employ the vehicle surround sound to convey the directionality of the nearby obstacles. This allows drivers to increase their awareness, especially for obstacles outside their field-of-view. We propose the VSS as an audio AR for alerting drivers of safety related situations.

4.2.1.1 Architecture

The system architecture relies on the constant beaconing provided by the DSRC-enabled vehicles, which provides an information-rich situational awareness. Figure 4.20 shows the architecture of VSS. When a Cooperative Awareness Message (CAM) [106] message with a special flag is received, the relative position of the respective vehicle is calculated and a synthetic sound is reproduced over the vehicle surround sound. The relative speed between the vehicles is used to shift the pitch of the sound in order to reflect the Doppler effect, while the distance is used to determine the volume of the sound. The osgAudio library [107] for the OpenSceneGraph (OSG) framework [108], provides features such as positionable listener and sound sources, attenuation and Doppler shifting. The framework is multi-platform and includes all the required features to implement VSS.

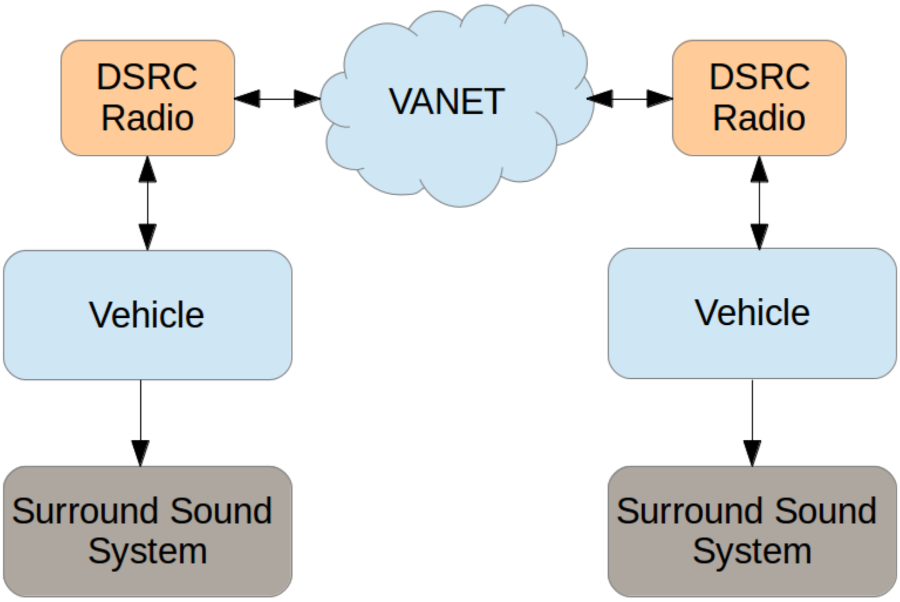

Figure 4.20: Virtual Surround Sound architecture.

4.2.1.2 System Applicability

This system allows for emergency vehicles to avoid using sirens in restricted zones such as nearby hospitals. Furthermore, a regular vehicle in an emergency situation could also alert neighbouring vehicles without requiring an actual siren to be installed in the vehicle. Figure 4.21 illustrates such emergency situation in a road intersection.

The VSS allows many more applications than just the emergency vehicle scenario, using acoustic AR to reproduce sounds tailored for each specific situation. For instance, vehicles equipped with emergency brake assist usually employ hazard warning lights with rapid blinking pattern, that are activated for several seconds after the emergency brake assist is used. However, these rear lights are effective for the car travelling immediately behind the braking car, being much less effective for other preceding vehicles. In fact, the CHMSL were designed to improve detection of the brake signal, by positioning it centrally in the visual field of trailing drivers, separated from other rear signals, as well as being visible through other vehicles [109]. The effectiveness of CHMSL is not limited to night time conditions and showed a long-term effectiveness in crash avoidance of 4.3% [110]. Using an appropriate CAM message that signals through DSRC the emergency brake event, we make the VSS reproduce a virtual tyre skidding sound in all vehicles in the Region Of Interest (ROI), parametrized by the distance to the braking vehicle.

Moreover, the VSS can be use in other possible dangerous situations such as low visibility

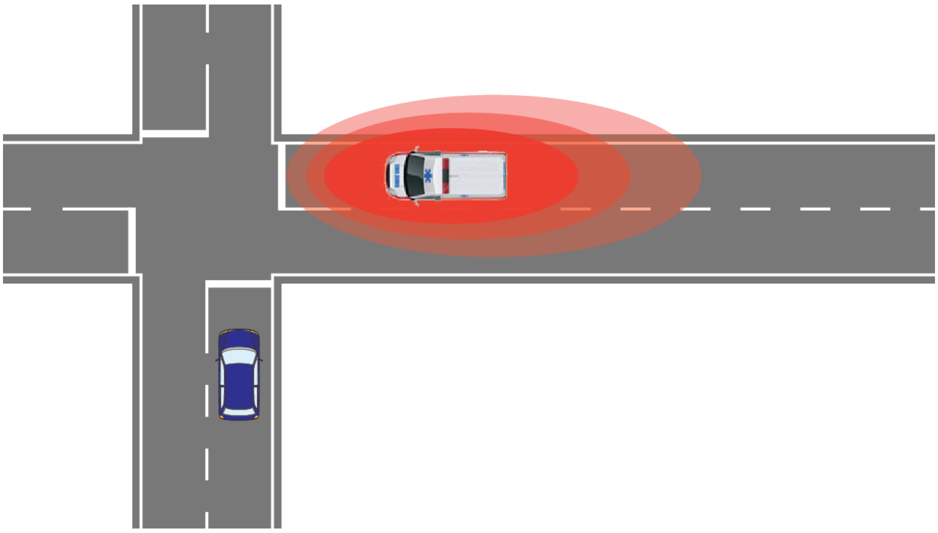

Figure 4.21: Emergency vehicle approaching an intersection.

situations. Chain-reaction crashes in highways can occur in low visibility situations like dense fog. VSS can prevent these collisions by propagating the information throughout the network that there is slow traffic or stopped vehicles ahead, and using or a tyre skidding sound or other type of sound that alert the driver. By simply relying on the VSS the driver can avoid crash collisions even without having visual perception of such situation.

4.2.1.3 Prototype

In our prototype implementation, a DSRC radio developed within the research project DRIVE-IN [111] is connected to a computer running an instance of OSG, with a listener profile representing the driver based on the current GPS position of the car. This computer is connected to a surround sound system that is also installed in a car. In a factory-installed system, the CAM messages would automatically set the VSS to overlay any other sound being reproduced by the sound system of the car. Low delay provided by the DSRC radios allowed to perform simple tests on a closed circuit. In order to verify if VSS was feasible, we tested two situations: emergency vehicle; and emergency brake. In the first situation, we assigned the emergency vehicle tag to a normal vehicle. When this vehicle has the emergency lights activated, it adds the "emergency" tag to its transmitted beacons. This beacons are received by the other vehicles, which use the position, speed and heading of the vehicle with the "emergency" tag to calculate the correct sound to play on the surround sound of the vehicle. Played sound combines all these variables to give a three-dimensional spatial positioning perspective of the emergency vehicle related to the vehicle itself. In the emergency brake situation, not only the "brake" tag is added to the beacons but also the deceleration rate of the preceding vehicle is transmitted to other vehicles. In this case, the system calculates the appropriate tyre skidding sound appropriate based on this deceleration and the distance between both vehicles. VSS detects if the system must be activated or not, by correlating the positions between vehicles, their direction and the events (e.g. brake).

However, due to the safety issues, the VSS must be evaluated using simulation. We implemented the VSS in the driver-centric VANET simulator described in Section 6.3, see Fig. 4.22. Due to both VSS and the driving simulator rely on the same technology, the evaluation results should be practically be the same in simulation and in road experiments.

Figure 4.22: Using the driver-centric VANET simulator to evaluate braking reaction times of drivers two cars behind the braking car.

4.2.1.4 Future Work

Preliminary evaluation tests using the simulator shown that the response time decreases substantially, being able to avoid the rear-end collision in all our experiments. However, more extensive simulation tests need to be performed to correctly evaluate the efficiency of VSS. Moreover, road experiments using VSS must be performed to validate the system in order to propose the VSS as viable and reliable audible AR ADAS.

4.2.2 Cooperative Awareness

The latest developments in ADAS are usually first introduced in high-end models and then get slowly deployed until they become mainstream vehicles. Therefore, looking into high-end models it is possible to predict how most vehicles will be equipped in the near future. With this perspective, we can observe that many of the latest ADAS are based on improving the surrounding awareness of the vehicle, such automatic braking assistance systems, lane departure warning systems, pedestrian collision avoidance system and others. VANET based on DSRC allow for vehicles to communicate with each other and exchange messages within a single hop distance. With CAM, vehicles inform neighbouring vehicles about their current position, speed, heading as well as its dimensions and type of vehicle. Furthermore, special flags can warn about collisions, approaching emergency vehicles and other road safety related information. While cooperative awareness should spawn new and cost-effective ADAS systems, it is greatly dependent on the deployment ratio of DSRC communications in circulating vehicles.

We propose the Computer Vision Aided Cooperative Awareness Messages (CVCAM) that exploits vision capabilities of ADAS systems in order to complement the DSRC based cooperative awareness. Note that the maturity of automotive computer vision system is quite high in comparison to vehicular communications. Hence, it is only natural to exploit these advanced systems in order to improve the effectiveness of DSRC based networks for low deployment scenarios. The system would work as follows: the connected vehicles with computer vision capabilities would first match the information obtained from the CAM messages in order to identify the other connected vehicles; Successive tagging would also yield relative speed and heading, assuming that the system is able to track multiple vehicles; This information would be broadcasted with CAM messages referring to other vehicles.

4.2.2.1 Architecture

The system architecture is comprised of the following elements:

- Windshield camera and other optional detection and ranging sensors;
- Computer vision system that combines the sensor data in order to identify and track objects within the field-of-view;
- DSRC communications device that exchanges CAM messages with surrounding vehicles;
- Display technology capable of augmented reality.

This system is represented in Fig. 4.23.

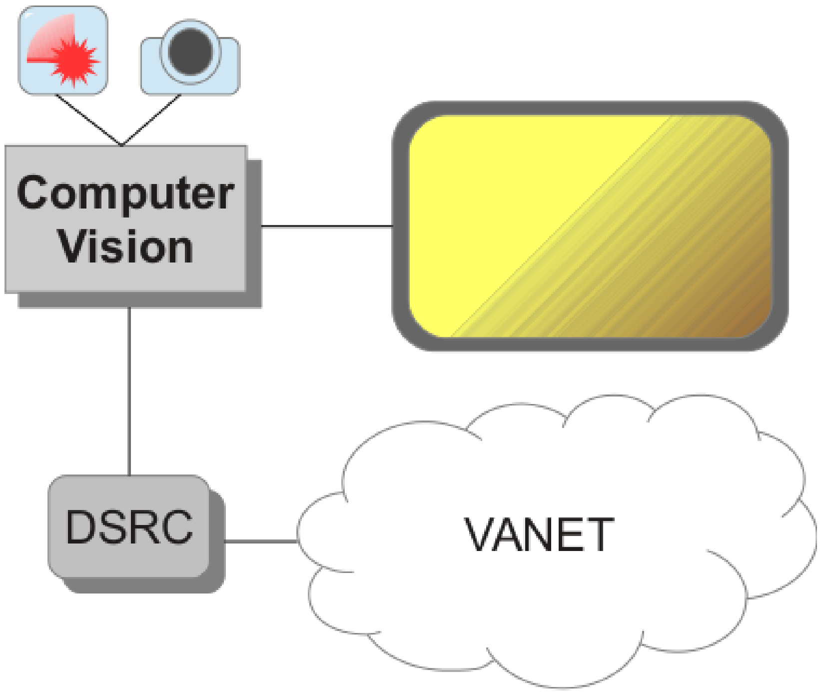

Figure 4.23: CVCAM architecture.

All these elements can be found in one form or another in existing systems, although this overall architecture provides innovative capabilities. First, the computer vision subsystem generates high-level information about detected objects that can be inserted into CAM messages. Second, the display subsystem converts this high-level information generated from local and remote sources (other vehicles) into visual information that can be presented to the driver and merged with the surrounding environment.

4.2.2.2 Human Machine Interface

A key element of the CVCAM system is the HMI, namely a transparent display system that informs about the CVCAM detected vehicles. The goal of the HMI is to provide a 360° awareness while maintaining the driver's focus on the road. Hence, the transparent display can be either based on virtual windshield technology [95] or smart glasses [98], and it is able to project pictograms and objects on the driver's vision in order to create an augmented reality system.

The display is composed of 3 main elements:

1. vehicle dynamics and navigation information such as speed, heading and engine revolutions per minute;

2. LOS vehicle information;

3. Non-line-of-sight (NLOS) vehicle information.

Figure 4.24: Example of a HMI for CVCAM using Vuzix® AR glasses.

The main challenge is implementing efficient solutions for improving the awareness of vehicles. For vehicles that are within the LOS, it is still important to provide extra information such as relative position, distance and speed. This can be provided in the form brackets for vehicles within the LOS. For vehicles outside the LOS but in front of the driver, this awareness can be provided by arrows running at the edge of the display. For vehicles behind the driver, this awareness can be provided by a virtual icons in the rear-view mirror that represent the type of vehicle and relative distance.

Figure 4.24 shows the HMI of CVCAM. As mentioned, LOS and NLOS vehicles are represented by brackets with arrows pointing out their distance and heading. Based on this new information, driver will be more aware of his surroundings. The CVCAM is particular effective on dense fog or adverse weather conditions, even though the lack of visibility in these situations. With CVCAM, surrounding vehicles are displayed on the windshield avoiding possible pile up accidents so common in highways in these adverse conditions.

4.2.2.3 Conclusions

We show that automotive computer vision can greatly improve the awareness of surrounding vehicles for DSRC-based VANETs with low penetration ratio scenarios. Furthermore, we propose an intuitive HMI for displaying high-level information about neighbouring vehicles to the driver. As of the case of STS, CVCAM is also one of the simplest examples where AR in vehicular environments provides useful means to reduce accidents on the road.

Chapter 5

Augmented Reality Driving: Sustainability

Achieving sustainability of transportation systems is a critical issue in modern society, and still unresolvable for the most part. Traditional approaches for achieving this goal focus mostly on reducing the expenditure with people, taxes, fuel or maintenance. Efficiency on spending has been the key.

We envision a new approach for sustainable transportation systems more focused on revenue generation. There are several industries that are mostly supported by advertising, including television networks, radio stations, and more recently most of the Internet sites. Our approach uses advertising for achieving sustainability of transportation systems. With VANETs, we are able to distribute advertisements using either V2V or V2I communication.

In this chapter, we propose two different applications based on this approach: an advertising system to support road infrastructures; and an advertising system to support public transportation systems.

5.1 Road Infrastructures

Roads in developed countries have become an infrastructure of very large proportions. The USA has the largest road network in the world, with more than 6.5 million kilometres in 2012. The EU road network has approximately 5.8 million kilometres, but much more densely distributed than in the US. With its 4.6 million kilometres in 2013, India has the second largest road network in the world. Furthermore, China's road network is rapidly increasing, already totalling more than 4.1 million kilometres in 2011 [112].

An analysis of the statistics in terms of road length, country area and Gross Domestic

Product (GDP) shows that, excluding very large countries in area (more than 650,000 km^2, approximately the size of France), almost all countries in the top 25 GDP list have more than 1 km of road length per km^2 of surface area. The only exception is Norway, number 25th in 2011 GDP list, with a much smaller ratio between road length and surface area of just 0.29 km/km^2. The top place belongs to Belgium (5.03 km/km^2), followed by the Netherlands (3.27 km/km^2) and Japan (3.20 km/km^2). Twenty of the countries in the top 25 list of countries by GDP are also in the top 25 list by length of roads. The exceptions are very small countries in area (South Korea, Netherlands, Switzerland and Belgium), plus Iran and Norway.

It is clear that the economy and society depend heavily on efficient road networks. Approximately 44% of goods transported in the EU go by road. Moreover, people travel mainly by road, with private cars accounting for 73% of passenger traffic in the EU[113]. Despite the importance of roads for economic growth, funds to build and maintain this infrastructure are typically under high political pressure, as they rely mainly on taxation over gas sales. Some US states have even considered introducing a special tax on fuel efficient vehicles in order to compensate for lost revenue. As a result, a 2009 report of the American Association of the State Highway and Transportation Officials (AASHTO) concludes that about 50% of the roads in the USA are in bad condition [7]. The EU has recently harmonised the level of taxes with minimum excise duties across Europe [114].

Toll roads are a common method of revenue generation for building and maintaining highways. The advantages are that users support most of the cost, even though cars subsidize the degradation caused by heavy transport vehicles. The main disadvantages are that alternative roads are usually burdened by vehicles that avoid paying tolls, with all the associated consequences in terms of accidents, road degradation and increased congestion. In trans-european road transport, some countries that have toll-free highways are especially burdened by traversing traffic from neighbouring countries. Other financing models include Public-Private Partnerships (PPP) where shadow tolls measure traffic and public funds cover the cost of tolls. These models have shown problems in terms of risk sharing mechanisms by placing an unequal burden on the public side [115]. Furthermore, demand for public transportation is also limited by the availability of highways with no cost to the user. Pay-as-you go schemes as an alternative to circulation tax have been proposed in countries such as the Netherlands, where users would be fitted with a GPS tracker that would charge an amount per distance depending on the road category and time of day. Public opinion has been strongly against this scheme, although similar schemes for car insurance have been welcomed.

We propose a novel and disruptive scheme for funding the road network infrastructure, based on revenues from virtual billboard advertising, that would leverage the emerging technologies of augmented reality on windshields and V2I wireless communications in the specially licensed 5.9Ghz band [2]. Our concept is to make virtual outdoor advertising very similar to the ads present in the most popular websites such as Facebook or Google, exploring personalised and contextualised content which greatly increases the added value of a virtual billboard when compared to the physical roadside infrastructure. In our approach, we envisioned using the concept of virtual windshield as a premium website, with a potential share of Internet time that reflects the average three hours of daily windshield exposure of American drivers [116].

Note that Internet advertising generates enough revenue for keeping free most of the online content, while paywalled websites usually struggle to generate sufficient revenue. The virtual billboards could provide a similar revenue model since they exhibit the same flexibility and targeted advertising of mobile ads without the constraints of the screen size, while typically reaching an adult audience with a reasonable purchasing power.

5.1.1 Billboard Advertising

The physical billboards placed on the roadside of an highway are exposed to thousands of visualizations per day. Nevertheless, most of these billboards display advertising that do not capture drivers attention, mostly due to the lack of relevance to the specific driver. The virtual billboard aims to provide an advertising that is relevant to the drivers by displaying a more contextual and targeted advertising tailored for each driver. In this section, we first describe the technical characteristics of outdoor billboards and then introduce the concept of a virtual billboard.

Outdoor billboards are also known in the advertising industry as bulletins. Due to its nature, a bulletin must comply to certain specifications. According to the Outdoor Advertising Association of America (OAAA) [117], the size of a bulletin must fit within 11-21 meters in width and 3-6 meters in height. Often, the shape of the billboard is modified in order to visually enhance some specific characteristic on the displayed advertising. Ads placed on these billboards usually stay in place during long periods, typically more than one month, and in Portugal such advertising costs about 700€/month. Digital billboards were introduced to provide a more flexible way to display advertising on a bulletin. While their format resembles the traditional billboard, their content can change more frequently, such as weekly, daily or even hourly. Furthermore, displayed ads are more dynamic, having the possibility to have embedded video and multiple layouts, within the limits imposed by local regulations.

To maximize the profitability of both billboard and the displayed ad, the placement of billboards takes into account its exposure time, in terms of visibility and number of different views. Usually, billboards are placed at the roadside of a highway, nearby populous areas, or on top of buildings. Still, the proliferation of billboards has been a real concern due to its visual pollution. Some U.S. states such as Alaska or Hawaii do not allow outdoor billboards, and in 2007 the city of São Paulo prohibited all outdoor advertising [118].

In terms of market share and exposure time, as shown in Fig. 5.1, out-of-home advertising represents a 27% of the consumer exposure time, even though it only generates 4.4% of the revenue. The information provided by [117] aggregates all out-of-home advertising and not just billboards. However, this further emphasises the disparity between exposure time and revenue.

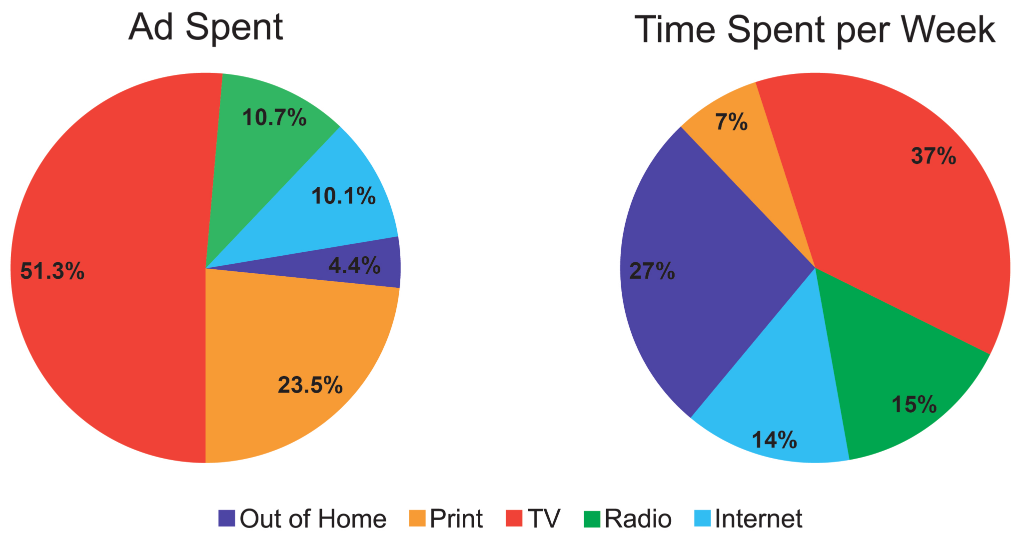

Figure 5.1: Market share and time spent per week for each advertising medium.

5.1.2 Internet Advertising

Since the early days of the Internet, there has been an exponential growth of both quantity and diversity of available content. This growth gained attraction from advertisers, that saw an immense opportunity to attract new customers to their businesses. Contrasting to the traditional out-of-home billboards or radio and TV advertising, the online advertising is more flexible by offering contextual and targeted advertising. Its dynamic nature attracted the advertisers to switch a substantial part of their investments from traditional to online advertising. This transition primarily emerged in the beginning of the 90's when the first advertising banners were sold [119]. Since then, the Internet advertising market increased exponentially to $7.1 billion in 2001 and $31.7 billion in 2011 in the U.S [120]. Some examples of Internet advertising are the display, social and search-engine results advertising. Key players on this market are Google, Yahoo, Microsoft and recently Facebook. The impact in terms of revenue is huge, with 96% of Google's revenue in 2011 coming from advertising services [121].

Most of the companies that provide advertising services use the cost-per-mile, cost-per-click and cost-per-view as theirs revenue models. Cost-per-mile model charges advertisers for every time an advertising is displayed, such as a web banner. Instead, with the cost-per-view model, the advertiser only pays when a user sees a video that contains the advertising. Furthermore, cost-per-click only charges when a user clicks on the advertising, as this model intends to drive the user to a specific website. Variables such as the content of a website, the content of a search performed in a search engine, the history of a specific user or its localization, are the base for the selection of a specific advertisement. Often, the advertising services use a cookie that tracks the history of a user, which websites he/she visited and ads that he/she saw or clicked before. In the case that users are using an account that is associated with a provider of these kind of services, the ads will be targeted with improved information such as their tastes or recent purchases.

Recently, with the advent of the evolution of smartphones, the advertising model has suffered some evolutions. Mobile advertising surpasses the Internet advertising in terms of contextual advertising. The inherent mobility increases the localization factor to select the best advertising to display. Furthermore, the different ecosystems that exist in smartphones such as iOS, Android or Windows Phone, enhance the advertisers with more rich data about the user tastes in terms of which applications, websites or places are being visited the most. However, the screen real estate is a serious issue within the mobile advertising, where there is a limited size available for the advertising banner. Another serious concern, are the unbearable costs associated with the Internet traffic inside the cellular network. In the past, Federal Communications Commission (FCC) addressed a similar issue with the prohibition of the FAX spam that proliferated in the 1980's [122], which implicated high costs to the user. The recent trends show that smartphones have already surpassed the traditional computers in terms of units sold. Therefore, it is expected that the growth of mobile advertising will level the internet advertising and eventually overcome it.

Note that drivers are the main target audience of a radio advertising, especially daily commuters. However, it cannot provide localized and targeted advertising that is possible on the Internet. This could change in the near future with the integration of Internet radio in connected vehicles, or the already announced Spotify services embedded in vehicles.

5.1.3 Modelling Highway Billboards

In order to propose virtual billboards, it is necessary to understand how these are distributed along highways. We identified all the billboards present in the A3 highway (Porto-Valença) on both directions, using a GPS logger and a webcam placed on the windshield recording the trip. We chose the A3 highway, due to be one of the most used highways that surround the city of Porto, and that can be used as model for highways in Portugal. The highway operator periodically reports on the volume of traffic data per segment of the highway. We obtained the linear regression model for the number of billboards $b_i = -5.988 + 0.001043v_i$, where v_i is the volume of traffic for segment i, with a coefficient of the determination of $R^2 = 0.9705$.

For each section, we obtained an histogram of billboards along the length of the segment divided into 10 bins, corresponding to equal 10% fractions. Afterwards, we added all the corresponding bins and obtained the overall distribution of billboards per segment. The latter presented a symmetrical pattern, so we collapsed the 5 higher bins into the lower ones, which allowed us to increase the data set and simplify the model to only half of the segment. Finally, we ran a distribution fitting algorithm and obtained the parameters for the closest model, which in this case was a negative binomial distribution with the parameters $r = 1.604$ and $p = 0.06374$. In Fig. 5.2 we compare the billboard data with the obtained distribution model.

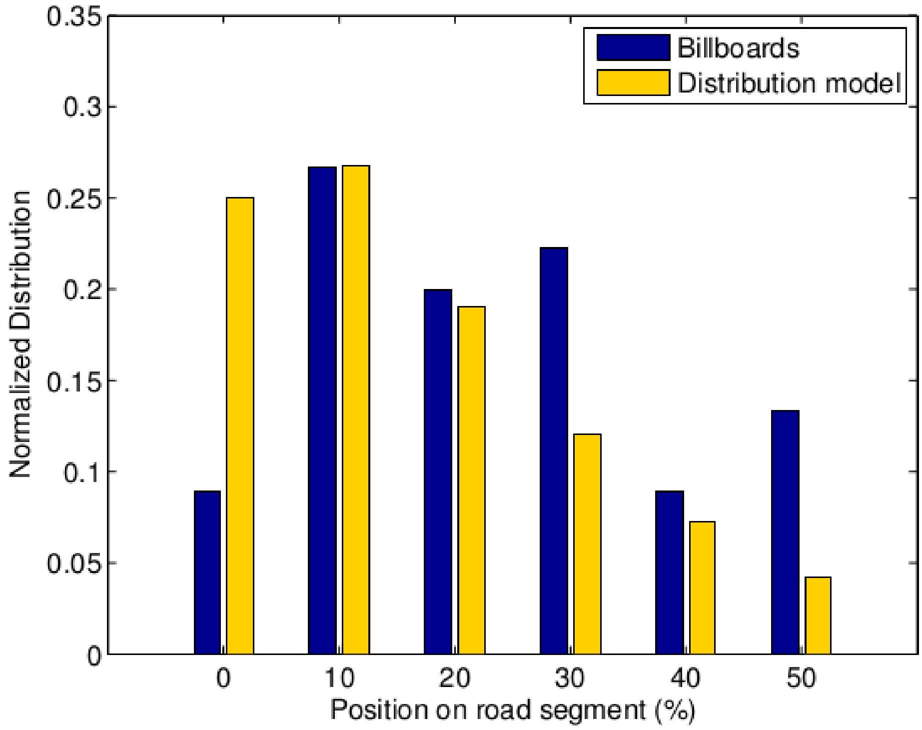

Figure 5.2: Comparison between actual distribution and obtained model [2].

With these two models we are able to estimate the billboard placements in other highways and create simulation models for the highway infrastructure in Portugal. Furthermore, it provides an insight into the rationale behind the placement of these billboards, namely that their number for each highway segment is proportional to the volume of traffic. Moreover, billboards tend to be placed just after an entrance and just before an exit. This rationale is consistent with the billboards content since they are usually advertising local products and services that can be found at subsequent exits of the highway.

5.1.4 Virtual Billboard

The architecture of the virtual billboard is built upon V2I communication between the vehicle and the billboard, as presented in the Fig. 5.3. To keep backward compatibility with existing roadside billboards architecture, the virtual billboard virtually superimposes existing billboards with the virtual advertising. Both vehicle and billboard must have a DSRC radio, and the billboard must be connected to the Internet and to an advertising network. Internet connection can be available on each billboard or clusters can be formed in order to share a single Internet connection for cost reduction purposes. By having each billboard connected to the advertising network, there is an unlimited number of advertisements to display. This advertising network will retain all the relevant information about each registered driver. Each vehicle advertises its driver's identification.

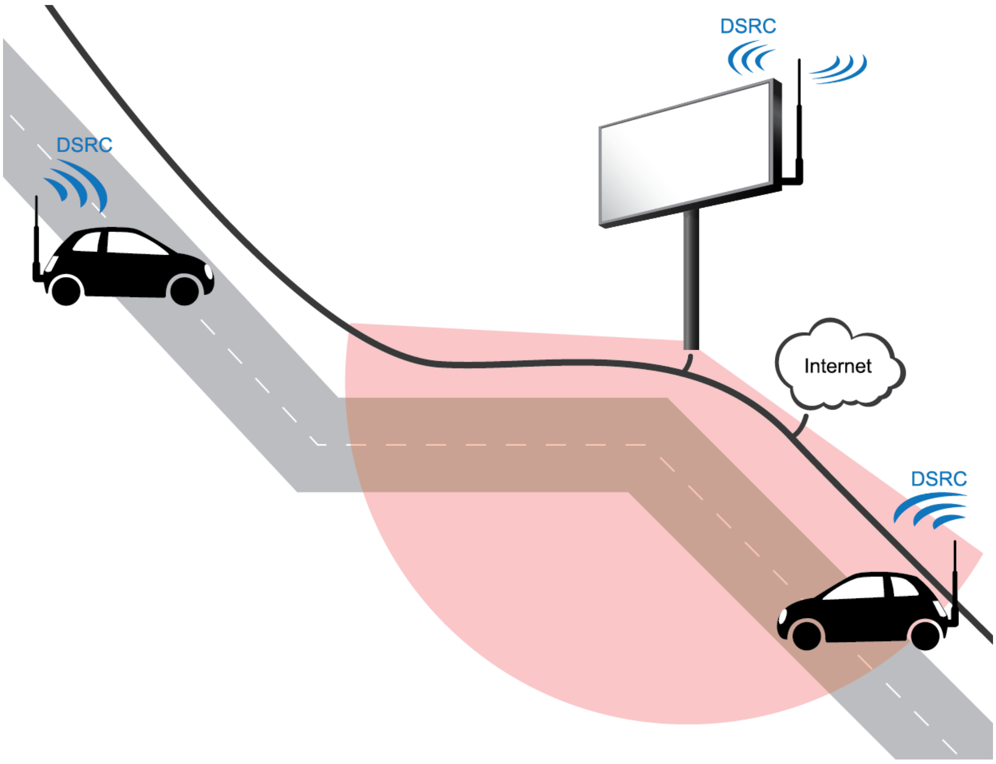

Figure 5.3: Architecture of the Virtual Billboard [2].

The selection of an advertisement is similar to current methods used on the Internet, using the driver's own personal preferences, advertising history, driving history, etc. This implies that each advertising displayed will have different variables to process, ultimately leading to different advertisings displayed on each vehicle that is within the visibility range of a specific physical billboard. In order to correctly create the virtual billboard, an accurate localization of both vehicle and physical billboard is needed. The vehicle can be in the communication range of the physical billboard but not in the visibility range since the visibility range can be affected not only by terrain obstacles like trees and hills, but also by environmental issues such as dense fog and rain.

The communication protocol relies on the periodic beaconing enabled in the DSRC radios, defined as CAM. Each vehicle periodically advertises its advertising network's user ID and its location. Upon receiving each beacon, the physical billboard evaluates if the vehicle is or will be in its visibility range. In that case, the user ID will be used to automatically select the best advertisement to be displayed on this particular vehicle. After this selection, the advertisement will be sent to the vehicle in order to be displayed on its windshield. Computer vision in the vehicle visually detects the position of the physical billboard in terms of the driver's point-of-view, and creates the virtual billboard by overlapping the physical billboard with the targeted advertising.

5.1.5 Proof-of-concept

Taking the concept of a virtual windshield previously introduced in Section 4.1.1, we envisioned the transparent LCD as the perfect way to enable the augmented reality within the vehicular environment. Based on this concept and in order to create a proof-of-concept, we performed an experiment based on video recording, computer vision and image overlapping. This experiment was performed on the same highway as in Section 5.1.3. We filmed the driver's perspective of the highway with a camera, with a resolution of 1280x720 at a frame rate of 30fps. This video allowed us to virtually reproduce the driving experience with a high degree of realism.

For this proof-of-concept, we created digital advertisements that superimpose on the existing roadside physical billboards. We assume that the physical billboards can either use a chromatic key technique or near-infrared markers that are easily detected by digital camera sensors. This billboard would then be detected using computer vision, assisted by GPS information and other characteristics transmitted by the billboard over DSRC. In each video frame, we replaced the physical billboard with a pink coloured billboard. We used the OpenCV library to programmatically detect it. By using the segmentation technique we are able to detect where the physical billboard is placed and then virtually replace it by a digital advertising. A sample snapshot of this representation can be seen in the Fig. 5.4.

We can observe the digital advertising correctly superimposed on the physical billboard, being seamless to the driver. The proof-of concept can be seen in video in [123].

Figure 5.4: Digital advertising superimposed on a physical billboard [2].

5.1.6 Billboard Sponsored Highways

In order to analyse the viability of billboard sponsored highways, we first obtain the toll-based revenue followed by an analysis of the advertising-based revenue necessary to replace these tolls. The equivalent cost per billboard for each highway segment was obtained by splitting the toll-based revenue by the number of billboards. This number was estimated by applying the model obtained in Section 5.1.3 to the A1 highway (Porto-Lisboa), which has 19 segments and about 300km. In Fig. 5.5, we present the daily cost per billboard for the actual toll values and compare it with the fixed price of 0.08€/km, which is defined by law as the reference toll price/km in Portugal. The values are ordered from lowest to highest in order to observe the number of highway segments that could become fully sponsored for different threshold values.

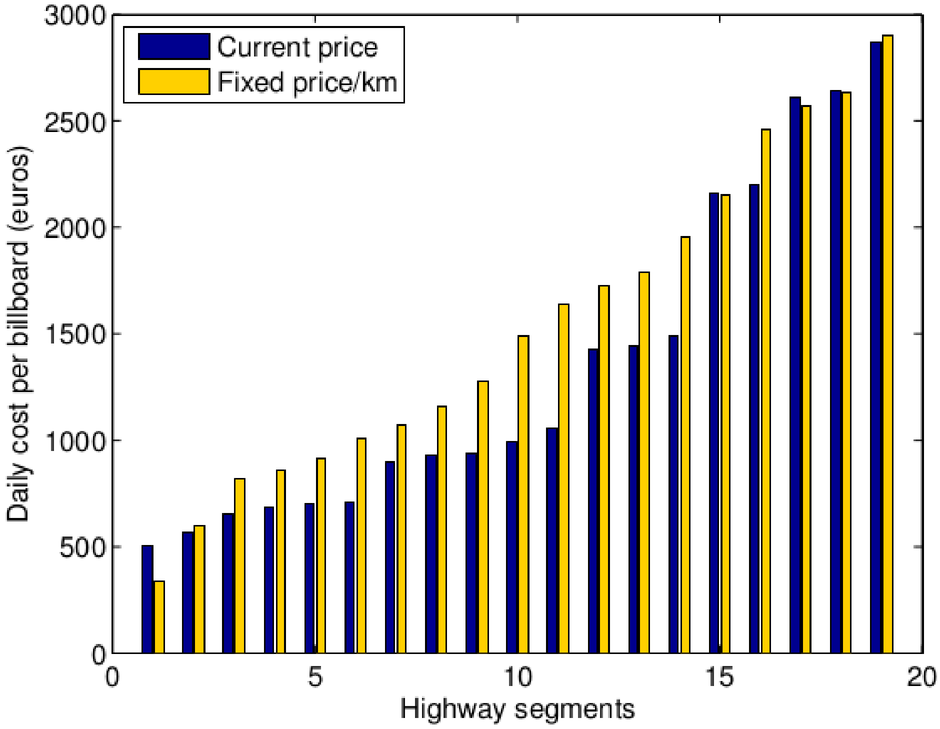

Figure 5.5: Equivalent cost per billboard for toll based revenue [2].

Since these billboards would provide targeted advertising, the daily cost per billboard should be analysed in terms of the number of views per day. Therefore, we obtain the billboard advertising cost per vehicle based on the number of vehicles for each highway segment. Furthermore, we analyse different scenarios in terms of the impact of switching from toll-based revenue to billboard sponsored revenue. First, it is reasonable to assume that removing tolls would increase the volume of traffic, since the inverse happened when Portuguese highways with shadow tolls switched to real tolls [124], with reductions up to 50% in the volume of traffic. Second, the billboard sponsored highway segments can either maintain the same revenue and absorb the increased traffic or reflect this increase in the billboard sponsorship, thereby generating an higher revenue. In Fig. 5.6, we present these different metrics for obtaining the advertisement cost per vehicle. We used the same ordering of highway segments as in Fig. 5.5 in order to provide better comparison.

These results show that 11 out of 19 highway segments could become fully sponsored and therefore free to users with advertising costs as low as 0.01€/vehicle. In Fig. 5.6, we observe that 11 segments stay below the threshold when considering a 50% increase in traffic due to providing toll-free highways. Even when considering a 30% increase in traffic and charging

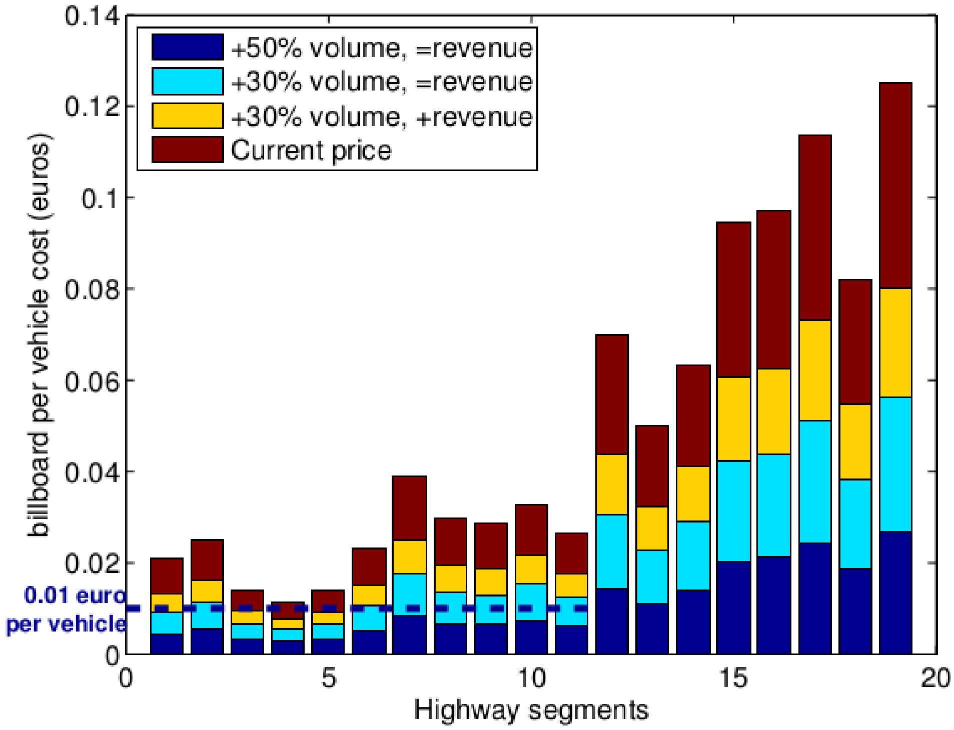

Figure 5.6: Advertising cost per vehicle for billboard sponsored highways [2].

advertisers for this extra traffic, the threshold would be around 0.02€/vehicle.

5.1.7 Conclusions

We present virtual billboards that combine the flexibility of Internet advertising, the contextual awareness of mobile advertising and the high exposure of roadside billboards. We present an architecture based on DSRC V2I communications and enhanced reality displays that allows for digital ads to be superimposed on existing physical billboards. We demonstrate the concept of virtual billboards using current technologies and present a video illustrating the system. Finally, we present the feasibility analysis of billboard sponsored highways and show that many highways with high volume of traffic could be supported from the advertising revenue alone.

5.2 Public Transportation Networks

Content distribution platforms for vehicular networks have been developed for public transportation systems such as buses and taxis. Similar platforms are already in place in many Rapid Transit systems, both at stations and inside vehicles, which usually provide infotainment and advertisement content. However, the economic viability of these platforms for other transportation systems usually depends on the cost of delivering new content to every vehicle, which can greatly differ from system to system. In cities where vehicles return to the same place at the end of the shift, content can be delivered via Wi-Fi without incurring in any data communications cost. This is usually the case for bus companies that service each vehicle and the end of the day. There are many examples of taxi companies that have similar structures. Nonetheless, it is more common to find umbrella organizations that aggregate privately-owned taxis and small fleets of vehicles, in order obtain critical mass for shared services such as dispatch systems. In this scenario, content delivery would typically require 3G communications since vehicles do not regularly concentrate in a few locations around the city. Note that 3G networks do not provide multicast services that would enable cost-efficient content delivery to simultaneous users. Hence, content has to be individually delivered to every vehicle when implementing 3G only solutions.

We propose a distributed content delivery platform for taxis that relies on DSRC for content dissemination, while using 3G communications for injecting new content into the network. We assume that taxis wait for passengers while parked on taxi stands distributed across the city. We assume that taxis already employ 3G communications for dispatch services and can also provide a control plane to the platform. This reduces the complexity of the system by excluding the scenario where some vehicles would only have DSRC communication capabilities. At the core of our system is a distributed algorithm that exploits the moments when vehicles are waiting for passengers at the taxi stands, in order to synchronize the content between these queues of vehicles. As taxis move across the city transporting passengers, they will eventually queue at different taxi stands throughout the day, hence providing an epidemic dimension to the algorithm. In [125] authors studied such type of urban mobility by using GPS traces of taxis in the city of Lisbon, Portugal.

This content delivery platform especially designed for taxi fleets incorporates Peer-to-Peer (P2P) file sharing features and is able to exploit the specific mobility patterns while addressing many of the problems faced with volatile wireless networks.

5.2.1 Content Distribution

Content delivery over IP networks usually relies on multicast services, where streaming multicast is used for real-time communications and reliable multicast for lossless content dissemination. Satellite networks present star-shaped topologies that make them especially suited for reliable multicast services [126] and have been used in many advertisement distribution platforms. However, terrestrial networks rarely support multicast services due to technical limitations, lack of commercial incentives or fear of flooding the network due to the multicast replication properties. Although 3G networks have a specification for Multimedia Broadcast Multicast Services (MBMS) [127], it apparently has no commercial deployments. On the satellite side, the S-UMTS [128] has been proposed for providing multicast services over large geographical regions, although with very limited bandwidth capabilities. The authors in [129] proposed an efficient and content delivery solution for vehicular environments.

In recent years, P2P content distribution has changed the content delivery paradigm, overcoming many technical difficulties such as server-side bottlenecks and asymmetric bandwidth connections. The basic idea is that a server only hosts a small descriptor file and the content itself is split into chunks and hosted by seeder nodes. A leecher node uses the information in the descriptor file to find seeder nodes and start downloading a chunk on each seeder. The P2P file sharing protocols include fairness algorithms that forces leechers to become seeders of the completed chunks. Beyond the basic functionality, several developments allowed for features such as real-time video streaming or completely distributed file-sharing systems, with decentralised descriptor files and search capabilities. In terms of VANETs, the Car torrent [130] was developed as a P2P file sharing protocol designed for vehicular environments. The Code torrent [131] is another P2P protocol with the added benefit of being based on network coding, which typically performs better in volatile networks such as VANETs. The AdTorrent [132] presents an integrated system for search, ranking and advertisement content delivery over VANET, with special focus on the vehicular mobility. While AdTorrent describes *Digital Billboard* as a location-aware advertisement, it does not mention how these ads would be presented to the driver or passengers. The SPAWN protocol is also a P2P content delivery mechanism for VANET, where RSU injects new content into the network that is then disseminated with V2V communications [133]. These different P2P protocols are just a subset of protocols that focus on delivering content over volatile vehicular networks with high mobility patterns. However, the early adopters of DSRC communications will probably be professional fleets of vehicles that want to invest in this technology in order to reduce communication costs of 3G networks. Hence, generic content distribution protocols may not present the best solution for these fleets of very specific vehicular networks, either presenting a mismatch between the assumptions and the actual scenario, or proposing overkill solutions.

5.2.2 Advertising Delivery Platform

We propose a platform for advertising content distribution for VANET, more particularly public transportation networks, such as taxi fleets. Due to its nature, the advertising distribution does not have tight time-constraint issues. Therefore, a delay-tolerant content distribution fits quite well the needs of our advertising delivery platform. In this section, we give an overview of our platform architecture and the algorithms responsible for delivering the advertisements.

5.2.2.1 Architecture

We propose a hybrid architecture based on 3G cellular network and DSRC communications to distribute new advertising content among all vehicles. This architecture can be seen in Fig. 5.7. We assume that all vehicles are equipped with 3G and DSRC communications. The advertising content is managed by an advertising network. This advertising network will not be addressed, but we can consider that its operation is similar to the ones existing on the Internet. This network uses the 3G communications infrastructure to deliver new advertising content to selected vehicles. DSRC communications allows us to distribute this content to other vehicles without using such infrastructure, thus reducing the unbearable costs associated with the 3G communications or other infrastructured communications. Furthermore, each vehicle is equipped with a GPS receiver to enhance the localization factor in the content distribution algorithm. This hybrid architecture provides the flexibility to minimize the costs without losing the ability to provide a high-efficient content delivery platform.

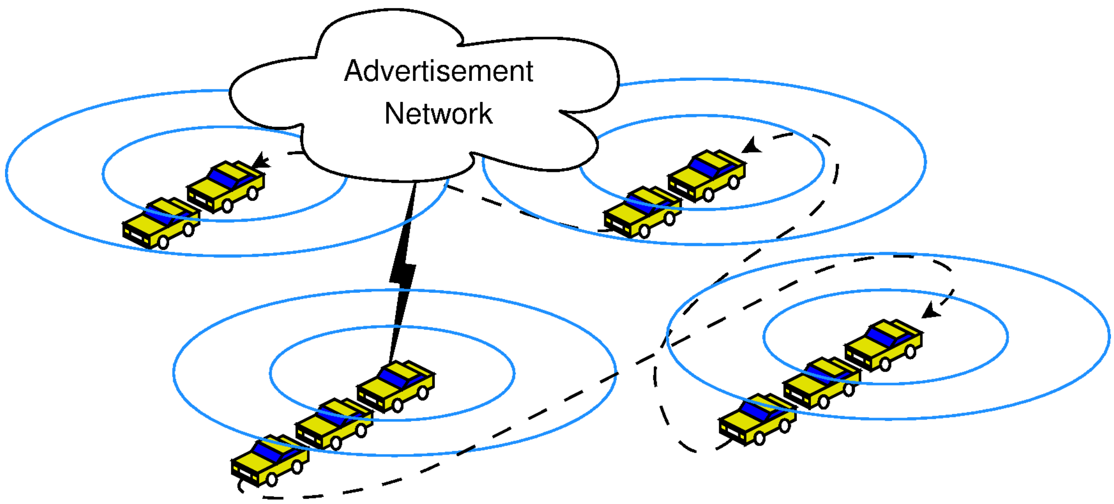

Figure 5.7: Vehicular advertisement delivery platform.

5.2.2.2 Algorithm

We propose an algorithm based on a set of heuristic techniques, since it is impossible to accurately predict the movements and the contacts of every vehicle in the platform. First, the content exchange is limited to taxis waiting for passengers in taxi stands. This allows for stable DSRC connections and content broadcast to multiple vehicles. Furthermore, taxis circulating in the city have very sporadic and short contacts between each other and may require DSRC communications for real-time critical applications. Second, the newest vehicle in the queue will only communicate with the last vehicle in the queue. The newest vehicle will push new content to the last vehicle and the other vehicles will also opportunistically receive it. Third, the newest vehicle will then pull content from the last vehicle in order to become fully synchronized with all the vehicles in the queue. By limiting the channel access to just two vehicles that communicate in a coordinated fashion, this mitigates the problems of medium contention in wireless communications. Finally, content is distributed in chunks with application level Forward Error Correction (FEC) in broadcast mode over DSRC to one or more vehicles. The use of FEC is a common approach when providing reliable multicast [126].

Figure 5.8 depicts the algorithm's flow diagram for content exchange. This diagram comprises two states in the taxi stand, the new vehicle and the last in queue. When a taxi arrives at a taxi stand it will be automatically assigned as a new vehicle and it will wait for the transmission token. This taxi waits for its turn to transmit, which only happens when previous content exchange stops and all the advertising content converges. Then the transmission token switches to the new vehicle. This new vehicle initiates communication with the last in queue by requesting its content list. With this list, the new vehicle is able to select missing advertisings chunks and sends them to all the vehicles in the taxi stand. After transmitting all missing chunks, it asks the last in queue for its own missing advertising chunks.

An open issue is choosing which reduced set of vehicles will receive new content over 3G communications, and which selection criteria will provide the fastest and most efficient delivery to the entire network of vehicles. These open issues will be evaluated using simulation with the VNS simulator in Section 5.2.4.

5.2.3 Taxi Stand Selection Criteria

We previously focused on the content exchange between the taxis inside the taxi stands, assuming that each vehicle has its own ads to be disseminated. However, this advertising delivery platform is based on a hybrid approach where new content is distributed for selected vehicles through 3G, which in their hand will continuously disseminate this information over

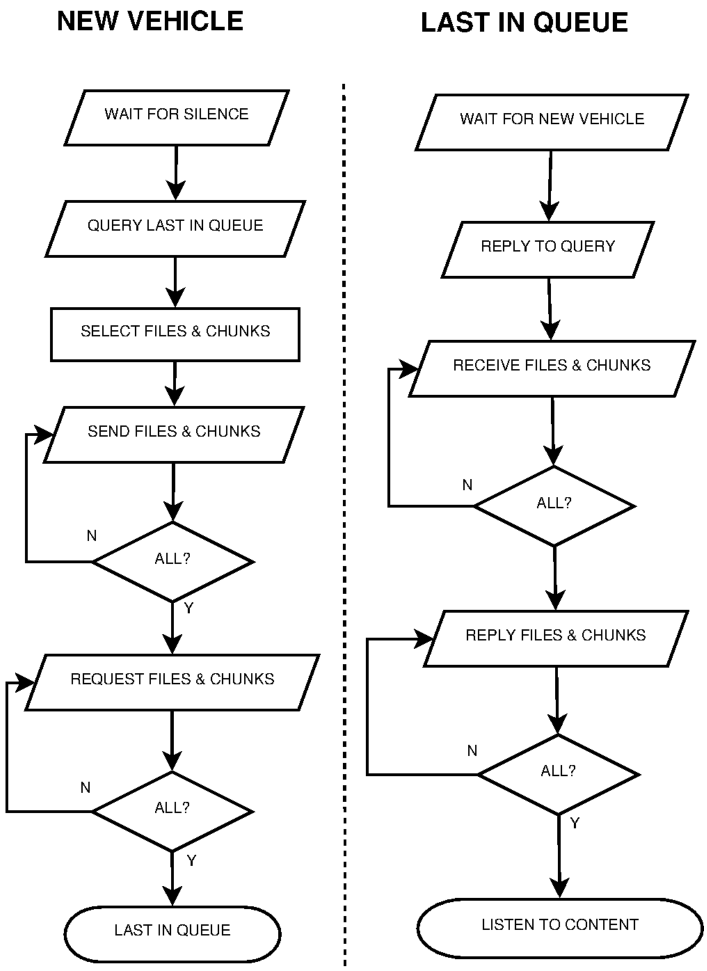

Figure 5.8: Algorithm for content exchange between taxis.

the taxi's network using DSRC.

Infrastructured communications, such as 3G or 4G, are an economic burden if they are used to disseminate large amounts of data across hundreds of nodes. Due to its nature of our advertising delivery platform, the data is delay-tolerant. Therefore, we can reduce the economic burden of using the infrastructured communications to deliver every single ad to each vehicle. Thus, in our hybrid approach we only select a subset of active vehicles to distribute the new ads through 3G. In Portugal, taxis are obliged by law to stop in a taxi stand in order to wait for services. Therefore, for a more stable and reliable data transmission using 3G communication, we chose to only distribute new ads when the taxi is stopped in a taxi stand.

The distribution of taxi stands across a large city varies accordingly with a diversity of parameters, such as population density, economical areas, hospitals, etc. During the day, these parameters are constantly evaluated by the taxi drivers, which use their knowledge to position in a taxi stand to obtain more services or longer services that give more profit. The selection criteria of what vehicles should receive the new advertisements is an open issue, which needs to be studied to see what fits best for this type of platform. Next, we propose different selection criteria to distribute advertisements to a reduced number of taxis.

- **Random Taxi Stands**

  In this approach, we randomly select a number of taxi stands across a city. This naive approach does not use any type of information from the taxi stands nor the taxis themselves. By randomly selecting the taxi stands which will receive new data, we expect that this approach will suffer from longer delays until the new advertisements reach every taxi in network. Due to its randomness, it can suffer from wrong selection, where taxi stands have zero or few taxis in stand for most of the time. Furthermore, selected taxi stands can be near each other, and will only distribute new advertisements for a few nodes of the active taxi's network. Thus, reducing the probability of equally distributing this new data throughout the rest of the network that is far from those taxi stands in a timely manner. We suspect that this approach will be discarded as feasible and effective for using in our advertising distribution platform. Figure 5.9 shows two cases of random selection of taxi stands. The left frame shows the selection of four taxi stands on the periphery area, where there is a lack of vehicles on taxi stands to receive the new data. On the right frame, the selected stands are close to each other, therefore the distribution of new advertisements will only be performed on a specific area of the city, thus reducing the probability of all the vehicles timely receive the advertisements.

Figure 5.9: Random taxi stands use case.

- **Random Taxi Stands Cluster**

  Contrasting with the previous naive approach, in this case the taxi stands are aggregated into clusters. The clusters do not overlap. Each cluster is composed by a number of taxi stands inside of a specific circle area closed to each other. Typically the circle's radius would be defined depending on the size of the city itself. The taxi stand in the center of each circle, will represent the cluster and receive all the new information. By aggregating taxi stands close to each other and with the location as the correlation factor, we expect that more vehicles will be receiving the new data, thus increasing the probability of reaching the rest of the network. In most cases, we expect that this approach will more effective than the previous one. Even though clusters can be near each other and focus only on a small part of the city, the number of vehicles receiving the new data will probably increase. In the Fig 5.10, we can see clusters randomly formed near each other on the left frame, covering a small area of the city. Furthermore, on the right frame we can see sparse clusters, that cover a broad area of the city. Still, due to the randomness of their location, clusters may not cover important and busier areas such as the downtown of the city.

Figure 5.10: Random taxi stands cluster use case.

- **Sorted Taxi Stands**

  The naive behaviour of previous approaches lack of information about the status of the taxi stands. In this approach the selection of the taxi stands takes into account the number of taxis parked at a given moment and/or the average number of taxis parked. This will dramatically increase the number of vehicles that will receive the data in a timely manner. Naturally, the number of taxis of a taxi stand selected to receive the new advertisements in a given moment can be large. Thus, the need to reduce the data distribution to a given percentage of the taxis in a taxi stand, in order to maintain the costs with cellular communication low. With this approach, the range of the vehicles getting new data will be higher than the previous ones. However, in some cases may tend to restrict the distribution to the vehicles that are in the downtown of the city, where typically the taxi stands have more vehicles parked. Figure 5.11 illustrates taxi stands chosen based on the number of vehicles parked at a given time of the day.

- **Sorted Taxi Stands Cluster**

  To face this restriction, clustering based on number of taxis parked in the taxi stands

Figure 5.11: Sorted taxi stands use case.

can improve the effectiveness of advertisement distribution. Instead of just selecting a few taxi stands based on this parameter, based on this information we can calculate clusters based on the average number of vehicles that each has and the number of aggregated taxi stands. In this approach, clusters can have different sizes to face the difference between the number of taxi stands in the downtown of a city, and in other parts of the city. We expect that this clustering approach will have a more stable behaviour than the previous non-clustering approach. Depending on the time of the day, clusters will cover different parts of the city, such as downtown, hospital or train stations. With this approach we avoid the selection of taxi stands near each other that have a high number of parked taxis. Figure 5.12 shows clusters formed based on the number of vehicles.

Figure 5.12: Sorted taxi stands cluster use case.

5.2.4 Evaluation

Performance analysis and comparison of the proposed content distribution selection criteria must be performed. Simulation frameworks are the perfect platform to perform extensive analysis over a number of scenarios. Therefore we used the simulation platform to analyse the content distribution in terms of both distribution and time to achieve different percentages of vehicles. For our simulation we used a realistic mobility model based on data collected from the testbed of taxis presented in Section 3.4. This dataset is provided by RadiTáxis, the large taxi fleet in the city of Porto, in Portugal. The same dataset was used for all the simulations. The dataset size varied with time and to be more accurate each evaluation was performed for different days of the week.

5.2.4.1 Simulation Setup

We used the Vehicular Networks Simulator (VNS) [134] as the simulation framework to perform our analysis and comparison. The VNS can simulate different scenarios and has the support for all kinds of datasets. Moreover, it is tightly integrated with NS-3 [135]. NS-3 has a module for IEEE 802.11p [14] specifically designed for vehicular communications. Thus, it is perfect for performing evaluation tests for this advertising distribution platform. Typically vehicular communications periodically transmit beacons that are specified by CAM. With CAM, vehicles inform neighbouring vehicles about their current position, speed, heading, and other type of information. Each vehicle stores this information in a location table with information about its neighbours. Table 5.2.4.1 describes the simulation parameters used in our simulations.

Simulations were performed on an Intel(R) Core(TM) i7 CPU 860 @ 2.80GHz, with 8Gb of Ram using the Ubuntu 12.04 operating system. We used the VNS 1.0 that combines both traffic simulation and network simulation with the NS-3.

5.2.4.2 Methodology

In order to evaluate the previously enumerated content distribution approaches, we used a dataset that consists of GPS traces of taxis from the city of Porto. This dataset has information about each vehicle such as: its identification; position; taxi stand status; and taxi stand identification. In this evaluation, vehicles only exchange advertising data and communicate with their neighbours when they are stopped at a stand. Selected vehicles receive new data through cellular communication. All simulations use the same dataset to maintain coherency and correctness of comparison between approaches.

The goal of this simulation is to understand how a hybrid approach like our advertising

Parameter	**Value**
RTS/CTS	False
BitRate	OfdmRate6MbpsBW10MHz
WifiMac Helper	NqosWifiMacHelper
WifiMac Type	AdhocWifiMac
WifiPhy Standard	802.11_10MHZ
WifiMacQueue MaxDelay	Conform to beaconing rate
WifiMacQueue MaxPackets	Maximum of 1 beacon
Propagation Loss Models	
Log Distance	ReferenceLoss: 37.35 dB
Nakagami	m0: 1.5, d0: 60, m1: 0.75, m2: 0
Propagation Delay Model	Constant Speed
DCF MinCw	15
DCF MaxCw	1023
DCF Aifsn	9
EnergyDetectionThreshold	-96 dB
TxPowerStart	16 dB
TxPowerEnd	16 dB

Table 5.1: Simulation parameters.

distribution platform can reduce the costs with cellular communications. In the Section 5.2.3 we proposed different approaches for introducing new advertisements in the network. Each approach will be evaluated in terms of percentage of the network with new data and the time needed to achieve it. For each approach, we perform simulations in which 5%, 10% and 15% of existing stands are selected to receive new information when the simulation starts. The last vehicle in queue receives this new advertisement data, which is then distributed using V2V communications to all the vehicles in the same stand. With this process, we eliminate the need to distribute the new data through cellular communication, thus reducing the costs. We performed simulations using real data from weekdays, with a 8 hour window from 06:00 to 16:00. Furthermore, we naturally assumed that a taxi is active for the entire shift and that has both cellular and DSRC communications capabilities. The city of Porto has 65 taxi stands and the average number of active taxis in each simulation is 278 taxis. The minimum distance between the cluster's center is 1000m, which corresponds to approximately 10% of the longitude of Porto.

The 3G network traffic for corporate users is usually priced in terms of overall volume, where individual users share a traffic pool. We assume a cost of 7.50€$/GiB$, based on typical commercial offers for corporate users, in Portugal for 2012. We assume that advertisements can be static images, audio clips and video clips. We define typical values for the size of the different formats, namely $200KiB$ for images, $1.2MiB$ for a $60s$ audio clip, and $20MiB$ for a $60s$ video clip.

5.2.4.3 Results

Simulations were logically divided in two categories: random; or sorted. On one hand regarding the random approaches, we performed 10 simulations for each day, in order to reduce the impact of the random factor when performing the comparison. In the other hand, as the data from a day does not change, we only performed a single simulation for the sorted approaches. Moreover, we initially thought that there would be a difference between distributing a single image, audio clip and a video clip. However, a taxi in Porto spends on average 46 minutes in a taxi stand waiting for a new service, thus for this evaluation we simplified and initially distributed a pack of images that totals the size of an audio clip.

First, we evaluate the behaviour of each distribution approach for a single week day. In order to perform the comparison, we calculated the average for the 5%, 10% and 15% of both random stands and random clusters approaches. Figure 5.13 shows the results of this evaluation.

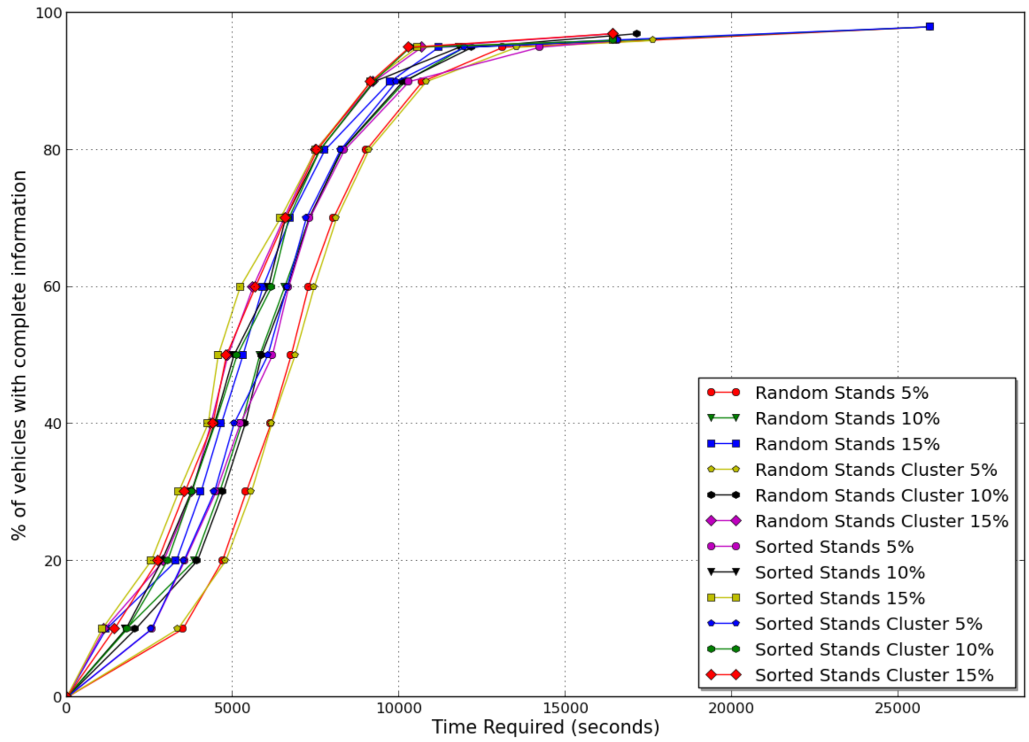

Figure 5.13: Evaluation results for one work day.

The first approach to reach 15% of the network was the Sorted Stands (SS) 15%, followed by the Random Stands Cluster (RSC) 15%, Sorted Stands Cluster (SSC) 15% and Random Stands (RS) 15%. The approaches' reaching order of 60% of the network is practically the same as of 15% of the network. 90% of network is reached first by the SS 15% and SSC 15%, simultaneously. Being followed by the SSC 10% and RSC 10%. The proposed approaches only needed approximately three hours to reach 90% of the network. When we analyse the 95% of the network we see that the sorted approaches with 15% of stands, continue to be the first ones to reach such percentage of the network, only being middled by the SSC 10%. All the approaches reach 95% of the network during the shift, and this is achieved by most of them before we reach four hours of simulation. Thus, 95% is achieved in just half of the duration of the shift.

By analysing the results, we found impossible to reach 100% of the network for this single shift evaluation. We assume that the missing vehicles are absent from the city's taxi stands or in peripheral taxi stands which do not make part of the usual mobility of the other taxis in the network. However, a few approaches reached 98% of the network, while the others reached between 96% and 97% of the network. Furthermore, based on these results we suspect that achieving a specific percentage of the network is more influenced by the taxis themselves than how we select the stands to receive the new advertising information. Even though some of the approaches achieve more rapidly the percentages, this conjecture is based on the assumption that the only time constraint is the shift.

Figure 5.14 shows the impact of each approach after 60s of simulation. This shows that after one minute, the vehicles that have received new information have disseminated to the vehicles in their stands and at least doubled the percentage of vehicles with this information.

Advertisement Type	**3G**	**5%**	**10%**	**15%**
Image	0.417	0.026	0.030	0.035
Audio Clip	2.502	0.153	0.180	0.207
Video Clip	41.700	2.550	3.000	3.450

Table 5.2: Comparison of data costs (€) between 3G communications and advertising delivery platform only reaching 95% of the network.

This evaluation allowed to show that using a small part of the vehicles to distribute advertising information in a taxi network can be feasible. Using 5%, 10% and 15% of stands resulted in a save of nearly 96%, 95% and 94%, respectively, of data transmitted using cellular communications to vehicles. Looking to the Table 5.2, we can rapidly observe the dramatic reduction of costs related to the cellular communications that this hybrid advertising delivery platform can provide. As our advertising delivery platform is not able to reach the 100% of the network, we add the costs regarding the completion using 3G communications.

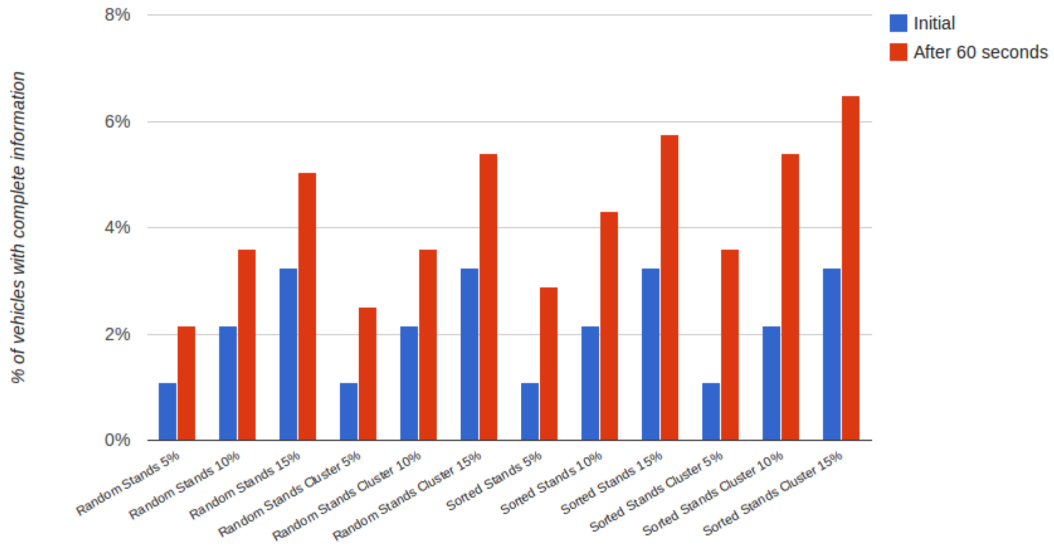

Figure 5.14: Advertising Delivery Platform performance after 60s (work day).

We performed an evaluation for a larger dataset in order to have more robust results. An evaluation of a week with 5 work days and considering the that mobility of the taxis will not change between different weeks. Furthermore, we did not took in consideration weeks that have some sort of special event, such as holidays or local parties. Figure 5.15 shows the evaluation results for this larger dataset.

We calculated the average of all the simulations and the results exhibit the same behaviour as the ones of one day. As expected SS 15%, SSC 15%, RSC 15% and RS 15% were the first approaches to reach 90% of vehicles with new information. Furthermore, we can highlight that sorted approaches behave better, and reached the network more rapidly than the others, followed closely by random approaches. Results show some slight changes in the order when reaching 95% of the network, but as expected, approaches that distribute new advertisements through 15% of stands have better performance. On average, it took just slightly more than three hours to reach the 90% of the network and four and a half hours to reach the 95% of the network. Thus, the results show that in half of the shift's duration we reach almost every vehicle in the network, and the ones that cannot be reached can receive the information through 3G communications. We consider this does not affect the validity of our advertising delivery platform due to the fact that we reduce more than 90% of the communication costs. Table 5.3 shows the comparison between the costs of distributing advertisements using each taxi stand selection criteria's average best result and 3G communications. As in our previous costs analysis, we add the costs regarding the completion using 3G communications.

We can observe that the costs of introducing a single video clip are unbearable using 3G,

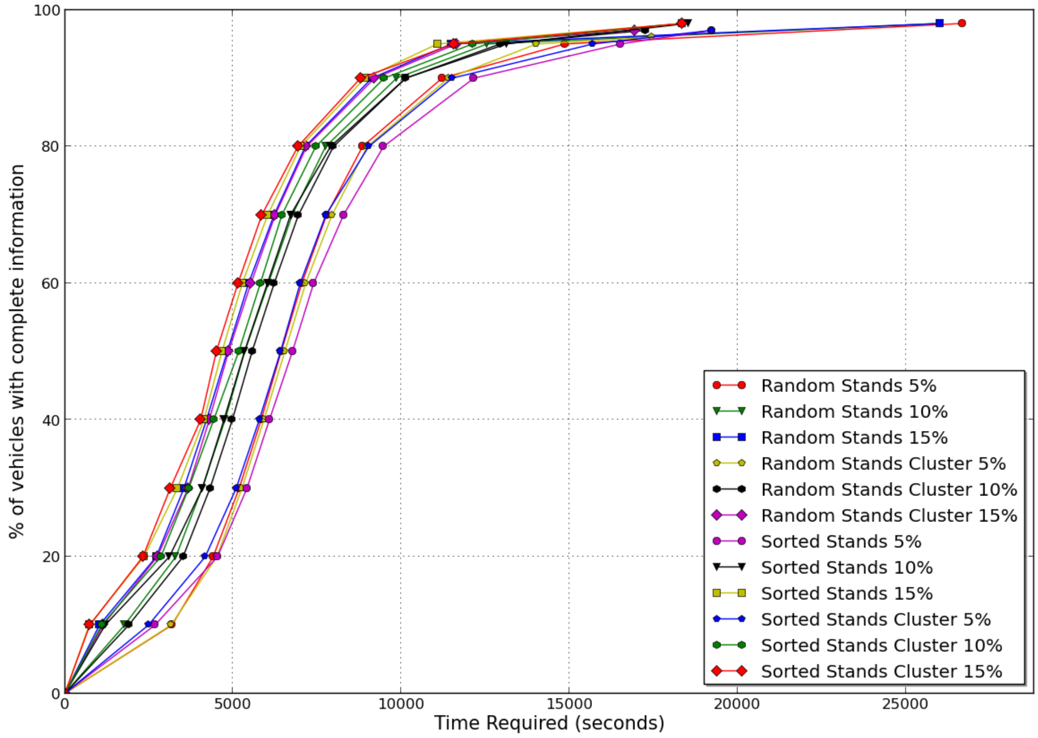

Figure 5.15: Evaluation results for one week (work days only).

costing more than 40€ comparing to the 2-3€ of using our hybrid platform. Using our platform distribute a video clip over the taxi network costs on average 2,06€, while an audio clip costs an average of 0.20€ and an image 0.02€. Our platform makes feasible to remotely distribute advertisements using 3G communications.

Figure 5.16 shows the effectiveness of this advertising delivery platform. In only one minute, it doubles the percentage of the vehicles that receive new advertisements, and it almost triples this percentage in the SS and SSC approaches.

5.2.5 Conclusions and Future Work

We present an advertising delivery platform that makes use of 3G and DSRC communications to distribute advertisements for a taxi fleet. We obtained a performance analysis and a comparison of the proposed content distribution selection criteria. Based on the results that we achieved, we can conclude that the selection of a taxi stand only affects how fast the information can propagate. However, results show that the time curve is identical between approaches. Taxis tend to cover homogeneously the city in order to get more services. Furthermore, when a taxi finishes a service, it tends to go to the nearest taxi stand to reduce

Advertisement Delivery Approach	Image	Audio Clip	Video Clip
3G	0,417	2,502	41,700
Random Stands 5%	0,014	0.081	1,350
Random Stands 10%	0,018	0,108	1,800
Random Stands 15%	0,023	0,135	2,250
Random Stands Cluster 5%	0,021	0,126	2,100
Random Stands Cluster 10%	0,021	0,126	2,100
Random Stands Cluster 15%	0,026	0,153	2,550
Sorted Stands 5%	0,021	0,126	2,100
Sorted Stands 10%	0,026	0,153	2,550
Sorted Stands 15%	0,030	0,180	3,000
Sorted Stands Cluster 5%	0,021	0,126	2,100
Sorted Stands Cluster 10%	0,026	0,153	2,550
Sorted Stands Cluster 15%	0,026	0,153	2,550

Table 5.3: Comparison of data costs (€) between 3G communications and the proposed advertising delivery platform approaches.

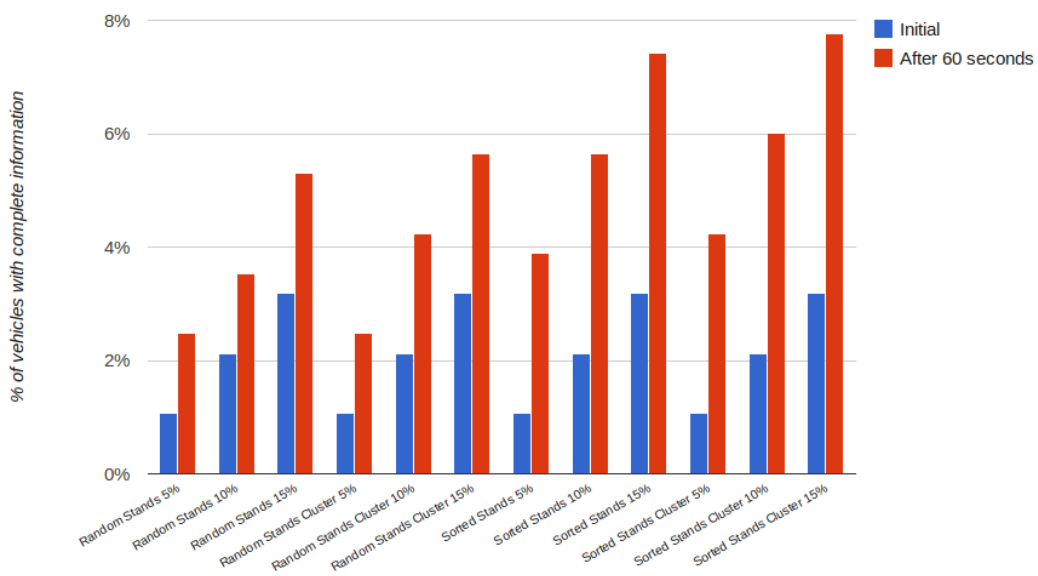

Figure 5.16: Advertising delivery platform performance after 60s (week).

the petrol costs. Thus, we can conclude that the mobility patterns of taxis is crucial for this platform. Information is disseminated equally, however the sorted approaches tend to perform better.

In the future, we need to analyse how the platform will perform with higher amounts of advertisement data. Also, we need to perform evaluations for different periods of day, and for different hours for distributing the new data.

Chapter 6

Real-time Driving Simulator

Existing VANET simulators provide a broad perspective of the network, aiming essentially at connectivity studies and protocol design, while disregarding the point of view of the of the VANET environment. In cases where, accidents, road congestion or other type of information that can influence the driving performance, and are transmitted over the network, both road traffic simulation and network traffic simulation concepts need to be combined [136]. Since the performance of field tests to evaluate innovative VANET applications could lead to dangerous traffic situations, it is not a viable test procedure in many cases. A driving simulator coupled with such simulators can reduce these difficulties and provide the right framework to test and evaluate such applications.

We propose a novel driver-centric VANET simulator that permits the evaluation of a number of VANET-enabled driver assistance and information systems. The driving is simulated in a VANET environment allowing the driver to interact with devices and applications that are communicating with the cars in his virtual vicinity. Our simulator builds on top of the open source microscopic traffic simulator DIVERT [137].

During this thesis work, we decided to take a different research path that focused more on prototyping the STS and on creating new ADAS that make use of vehicular communications. Due to this choice, this chapter lacks a more detailed evaluation of the different applications that were tested using the driver-centric simulator.

6.1 Related Work

Since it is crucial to test and evaluate protocol implementations on a large-scale realistic environment, studies of vehicular communication protocols in the VANET context are typically based on simulation models [138]. While a variety of simulation tools have been developed to analyse transportation scenarios at the micro and macro-scale levels, and in the last years the number of tools for integration in traffic and network simulators has rapidly increased [139], little effort has been devoted to the integration of communication techniques and scenarios in a realistic transportation simulation environment [140]. In [136], the need for bidirectional coupling of network simulation and road traffic micro simulation was discussed and the hybrid simulation framework Veins was introduced. VANET research has also made available tools to facilitate the rapid generation of realistic mobility models for simulations [140] like in modular integrated traffic and network simulators [141] and microscopic traffic simulators on the real maps of cities such as Porto [142]. In addition, other open-source simulation environments have been introduced for proper evaluation of protocols for VANET [139] and new scenarios including online virtual worlds have been suggested to conduct driving simulations [143].

Research has shown that driving simulators are proven to be excellent practical tools to test ADAS or Driver Information Systems (DIS) [144]. There has been a lot of research and an equally large amount of efforts in modelling concepts and techniques for improving behavioural intelligence and realism in driving simulation scenarios. For example, the authors in [145] developed neural driver agents to learn and successfully replicate human lane changing behaviour based on data collected from a car simulator [146]. Other techniques like Artificial Neural Network (ANN) models have also been used in the development of simulators, data collected from highways in Saudi Arabia was used for estimating headways in vehicles [147]. These models are capable of learning from training examples and demonstrating learned behaviour in imaginary situations. In spite of all the new features that have been incorporated to the vehicles in the last years and the high realism reached in the current simulators on the market, the interaction between the driver and the vehicle has not changed significantly.

6.2 VANET Simulator

Realism is a crucial aspect of a driving simulator, specially if it is designed to test and evaluate innovative driver assistance and information systems. Therefore, we use above mentioned VANET simulator DIVERT to populate with vehicles the road network that is used in our driving simulator.

The DIVERT is an open-source microscopic simulator written in C++ that allows micro-simulation of thousands of vehicles with a high degree of realism. It has tools that allow to recreate all types of the road environments and situations. A complex scenario editor allows to define road segments at the lane-level, describing detailed connectivity at intersections and traffic-lights functioning. The DIVERT allows to define individual parameters that affect the behaviour of the simulated vehicles, such as aggressiveness, braking and acceleration patterns, or patience threshold. Moreover, different vehicle types can be defined (e.g. truck, bicycle, ambulance) as well as their individual routes. Different map formats (e.g. Tiger, OSM) can be imported, which allows to test almost every city in the world.

Figure 6.1 shows the overall architecture of DIVERT, which depicts its tight integration with the NS-3 [135]. NS-3 is widely used by the research community and has been correctly validated. It provides various protocol modules, real-world integration and has a stable design for improved scalability, being capable to simulate large scale scenarios and high traffic densities. Several radio access technologies such as 802.11p, UMTS or WiMAX can be used in simulations. Later, this framework was redesigned from scratch to fulfil the simulation requirements of modern VANET applications, and evolved to the VNS framework [134]. However, the illustrated architecture represents the basis of the VNS framework at the time of this work, and thus, we use the name DIVERT to refer to the VANET simulator.

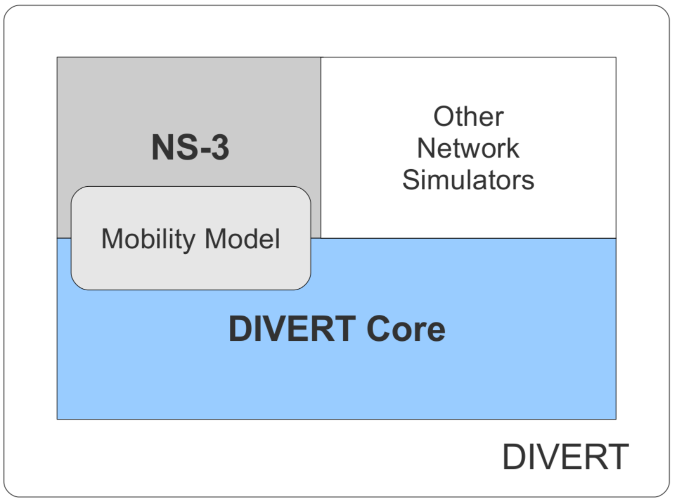

Figure 6.1: DIVERT architecture

Figure 6.2 depicts the simulation execution behaviour of DIVERT and NS-3. At each simulation step, the DIVERT's step is executed and after its conclusion, the correspondent step is executed in NS-3. This coherence is crucial, even though steps may vary in their processing time, they always maintain this behaviour. Nevertheless, the simulation is always controlled by DIVERT itself, which decides all the simulation parameters. Next, we describe an essential part of DIVERT, its traffic flow model.

6.2.1 Traffic Flow Model

The DIVERT traffic flow mobility model is based on the Intelligent Driver Model (IDM) [148]. In the IDM model the acceleration is expressed as a continuous function of the velocity v_0,

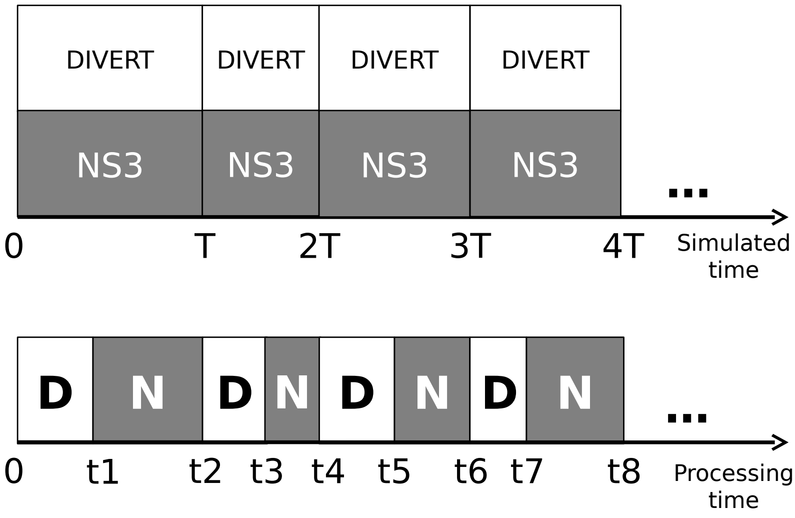

Figure 6.2: Simulation execution

the space between the vehicle α and the vehicle in-front and their approaching rate. The equation 6.1 expresses the velocity of a vehicle defined by this model. Table 6.1 describes all the parameters of the IDM model.

$$\dot{v_\alpha} = a^{(\alpha)} \left[1 - \left(\frac{v_\alpha}{{v_0}^{(\alpha)}} \right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right)^2 \right] \tag{6.1}$$

Parameters such as acceleration depending on the traffic situation can be expressed by the equation 6.2.

$$a_f(v_\alpha) := a^{(\alpha)}[1 - (v_\alpha / {v_0}^{(\alpha)})^\delta] \tag{6.2}$$

Deceleration from the vehicle α depends on the required space to the vehicle in front (s^*) and the current space between both vehicles (s_α). The equation 6.3 describes the relationship between the parameters.

$$s^*(v, \Delta v) = {s_0}^{(\alpha)} + {s_1}^{(\alpha)} \sqrt{\frac{v}{{v_0}^{(\alpha)}}} + T^\alpha v + \frac{v \Delta v}{2\sqrt{a^{(\alpha)} b^{(\alpha)}}} \tag{6.3}$$

These model expressions denote a pre-defined or randomly generated route for the cars to follow. They determine if the car needs to adapt the velocity to the current road conditions (i.e. encountering an obstacle ahead). The behaviour of the vehicles behind is specified by the cars ahead.

Parameter	Description
v_0	desired velocity
T	safe time headway
a	maximum acceleration
b	desired deceleration
δ	acceleration exponent
s_0, s_1	jam distance
v	velocity
α	vehicle
v_α	vehicle velocity
s^*	vehicle in front
s_α	space between vehicles
a_f	acceleration on a free road

Table 6.1: Description of the IDM parameters

6.2.2 External Vehicles

The VNS framework, a totally rewritten version of DIVERT, introduced support for external controlled vehicles. This module was developed taking in consideration the needs of a driving simulator. Figure 6.3 depicts how this module fits on the top of the VANET simulator.

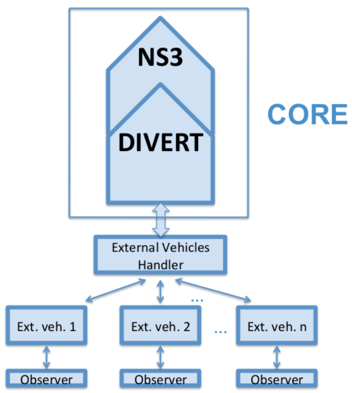

Figure 6.3: External vehicles support.

Coupling the vehicles from the driving simulator and the VANET simulator requires a synchronization of the mobility behaviour of both simulators. The performance of the driver in the driving simulator affects the behaviour of the vehicles consequently the mobility model of the simulated vehicles in the VANET simulator. The placement of an external vehicle operated by the human driver in the driving simulator modifies the behaviour of the car-following model used by the VANET simulator. The simulated vehicles need to adapt their speed to the speed of the new object and thus their mobility patterns. Thus, the speed of the simulated vehicle is adjusted to avoid collisions with the inserted vehicle through additional acceleration and deceleration parameters. The vehicles can then respond to new mobility patterns such as being able to stop when the simulated car from the in-vehicle driving simulator stops.

6.3 Driving Simulator

The driver-centric VANET simulation framework is an advance in the existing current evaluation tools for VANET and ITS applications, since the driver is immersed in a vehicular environment that is provided by the above mentioned VANET simulator. It aims to fill the gap between existing VANET simulators and driving simulation platforms, providing a driver-centric perspective of VANET-enabled applications and becoming a fundamental tool for the research, validation and evaluation of ADAS. This driving simulator is essential for testing innovative applications that are dangerous to evaluate in real-world situations, such as the STS [16].

6.3.1 Architecture

The implementation of a realistic driver-centric simulation tool that allows the validation and evaluation of such applications demands the design of an interface for coupling the driving simulator with the VANET simulator. The proposed architecture uses a Transmission Control Protocol (TCP) connection to link the driving simulator with the VANET simulator.

The diagram in Fig. 6.4 illustrates the coupling architecture between the VANET simulator and the driving simulator. The simulation platform consists mainly of three components: the VANET simulator; an in-vehicle realistic driving simulator; and an interface able to couple both.

6.3.1.1 DIVERT Simulator

DIVERT provides the variety of traffic scenarios in respect to the microscopic mobility characterization of simulated vehicles, together with a network simulation layer that models the wireless channel and ensures that the information is routed towards the location where it is most useful. In addition a TCP server allows the integration of simple modules to communicate with external applications. DIVERT includes a complex editor of traffic entities

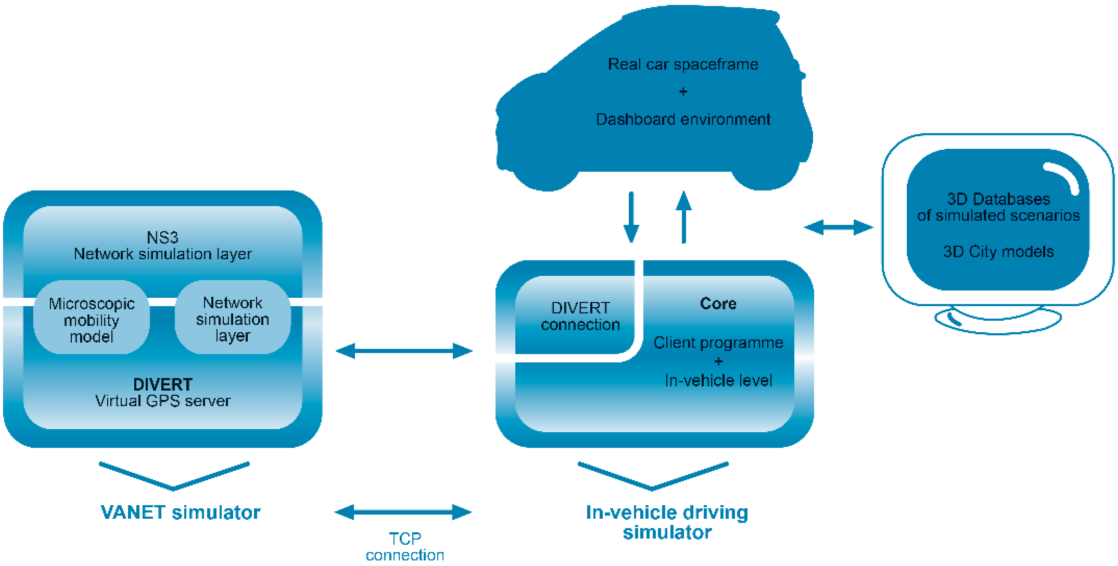

Figure 6.4: Driver-centric VANET simulator architecture

where road segments can be defined. The microscopic realistic traffic simulator is capable of capturing the complexity and detail of the vehicle' trajectories that suit a wide scope of perspectives. To enhance and refine the traffic flow modelling much more detailed properties are required, that are able to provide a realistic feeling for a human driver guiding a vehicle through the client program. Thus, the Driver-Centric VANET simulation platform aims to significantly enhance the mobility patterns of the individual vehicles from the DIVERT simulator by taking in consideration the unpredictability of the driver.

6.3.1.2 In-Vehicle Driving Simulator

A key element of the Driver-Centric VANET simulator architecture is an in-vehicle environment that is fully equipped with driver interfaces able to convey information provided by VANETs. This environment guarantees a realistic interaction between the driver and the system. The physical simulator platform was built on an engineless Smart Fortwo car [149], and consists of the following components:

- Cockpit with all controls;
- Steering wheel;
- Acceleration and braking pedals;
- Driver's car seat;

- Dashboard with instruments;
- Windshield for projecting information;
- A portable display system for easy assembly at any location;
- Sound system.

In addition we incorporate to the platform a Head-up Display (HUD) to represent advanced in-vehicle signs. The multimodal interaction with the system through manual controls, touch screen, voice, maps or lights, ensures a natural control and efficient use of the integrated applications.

The driving simulator is written in C++ for processor and memory efficiency. The computer graphics of the driving simulator are based on the OSG [108] library, since it provides all the support for different scenario visual perspectives, in particular from the inside vehicle viewpoint. Along with the OSG, we used the Bullet physics library [150] to provide the realistic physics associated with the driving task and the simulated scenarios. Each driven vehicle has several variables, such as its acceleration speed, horsepower, torque, power curve, maximum speed, weight and dimensions. All these variables are used to provide a better driving experience and thus effectively provide the best driving simulation environment to test applications.

A desktop computer allows operating the simulated vehicle using a simple client program. The client component includes 3D databases of the simulated scenarios. We designed some city models that supports simulated driving experiments and allows to improve the mobility patterns from the vehicles simulated by DIVERT. Figure 6.5 illustrates the simulated urban scenario from the city of Porto populated from the DIVERT environment. The in-vehicle driving simulator is shown in Figure 6.6.

6.3.1.3 Coupling Interface

The coupling interface stands on one assumption, the base map of the simulated scenario is similar on the driving simulator and DIVERT. Both applications need to share the same coordinate system, so that an accurate car trajectory can be assured. The scenario elements, namely, the roads, traffic signs, buildings, trees and other road objects, are populated based on their geographical position from a 3D objects database.

The coupling architecture itself is a typical TCP client-server architecture, where DIVERT acts as a virtual GPS server, providing rich data sets gathered by GPS receivers, such as vehicle's position, heading and speed information of each vehicle being simulated. Since DIVERT provides a TCP server thread for external applications and the in-vehicle driving

Figure 6.5: Simulated urban environment from the city of Porto populated from the DIVERT road scenario.

Figure 6.6: Research Driving Simulator of the Computer Science Department of the University of Porto.

simulator is implemented as an autonomous external application, both can be easily connected. In this context, the driving simulator acts as a client which connects to DIVERT to get information related to each simulated surrounding car. Any action performed by the driver in the driving simulator affects all his neighbours in DIVERT, as explained in Section 6.2.2. This coupling interface was developed in collaboration with the authors of the DIVERT [137].

6.3.2 Data Exchange Protocol

In this section we detail the data exchange protocol that makes possible the simulated VANET environment from a driver-centric perspective. This protocol comprises the driver's vehicle creation, update and deletion.

- **Vehicle Creation:** DIVERT receives the information related to the vehicle operated by the human driver in the driving simulator, namely its dimensions, current position, heading and speed. This information allows us to fit the data points into DIVERT locating and creating a new vehicle in the corresponding map coordinates. To locate the vehicle in the correspondent coordinates, we obtain the nearest road to the point efficiently, relying on spatial information technology for indexing multi-dimensional information. The data structure consists of nodes that have a variable number of entries. These entries store a child node identification and a bounding box of all entries within this child node. Each tree node corresponds to roads containing the information related to the lanes that constitute the road. The vehicles are bounded in the lanes, thus making it possible to select the nearest neighbours of the driver's vehicle in the driving simulator.

- **Vehicle Update:** A periodical update of the transmitted data set coming from the vehicle in the driving simulator is performed and sent automatically to DIVERT. These new values are then distributed to the neighbour vehicles, thus resulting in an update of the relevant parameters: vehicle identification, position, heading and speed. The new values related to the vicinity nodes of the driver's vehicle are then sent back to the driving simulator.

- **Vehicle Deletion:** In order to be capable of ending the driving simulation the data points related to the vehicle in the driving simulator need to be removed from DIVERT. Therefore, the relevant information is sent to DIVERT and it is deleted from its simulation. Afterwards, the vehicle is no longer visible to both simulated vehicles or other driver vehicles. A final confirmation is sent to the driving simulator, which successfully terminates the application.

6.3.3 3D Representation of Vehicles from DIVERT

The process of fitting the data points from DIVERT into the driving simulator is equivalent to the previously described. At the same time we start the driving simulator, the driver's vehicle is created in DIVERT, which replies with the data points corresponding with vehicles from DIVERT in the vicinity. When the driving simulator receives such vehicle's data points from DIVERT, a new 3D object matching each data point's parameters is created in the corresponding coordinates. Therefore, we ensure that each simulated car that appears in the in-vehicle driving simulator maintains the current position and heading from DIVERT. At each step both the in-vehicle driving simulator as well as DIVERT keep synchronized in terms of actual position, heading, and acceleration. The data exchange protocol used in our approach allows to populate the driving simulator with vehicles from DIVERT with the warranty and reliability of the simulated vehicles' data. In addition this approach allows us to calculate new data points in a simple and efficient way minimizing the introduction of errors. The next section describes the data synchronization between the coupled simulators in more detail.

6.3.4 Data Synchronization

In our approach, we split the coupling interface into two running tasks, running on the driving simulator application and on the DIVERT simulator respectively. Our approach allows the task from the driving simulator application to continuously receive the position coordinates and other relevant information of the neighbour nodes from DIVERT and at the same time to send the location, heading and acceleration of the car operated within the driving simulator directly to DIVERT. The data exchange protocol maintains some dependencies between each running task, in particular when data is sent from the in-vehicle driving simulator to DIVERT or other way around. In both cases the TCP client-server threads wait for the information from the other simulator. This behaviour is crucial for the coupling since it is precisely this send-wait-response protocol that causes the thread data synchronization in both threads to occur without any kind of positioning error neither in DIVERT nor in the driving simulator. Figure 6.7 illustrates the synchronism of the execution of both simulators.

Being based on TCP client-server architecture, the data exchange protocol allows having warranties on the delivery of each packet sent by both applications. The process assures synchronism in the simulators' coupling and enables coherence on the driver vehicles in both applications.

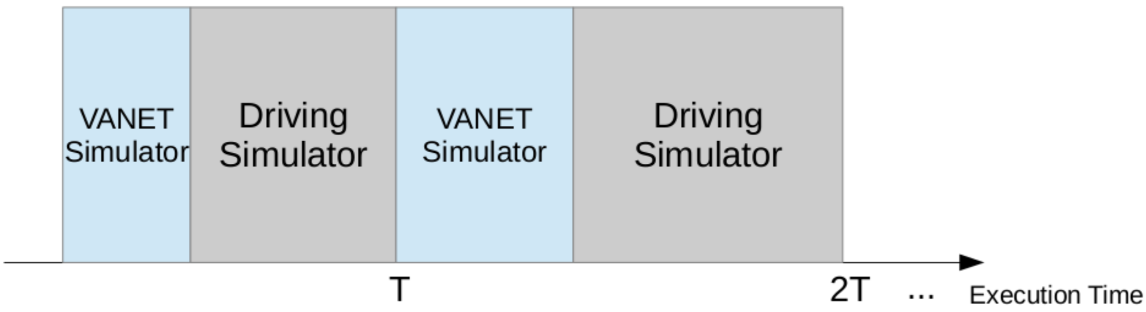

Figure 6.7: Simulation execution of VANET simulator and driving simulator.

6.3.5 Driving Simulator Implementation

Testing real-time vehicular applications using simulation demands for a reliable framework that mimics the driving task. Our primary goal was to design a driving simulator that was able to exactly reproduce the driving experience. The simulator was developed using C++ in order to meet the performance requirements of such driving simulation framework. The visual part of the simulator is based on the OSG [108]. It provides a high-level 3D graphics Application Programming Interface (API) that allows to render the different agents of a simulation more simply than using directly OpenGL [151]. The software uses the scene graph approach to representing 3D worlds as a graph of nodes, where each object in the scenario (vehicle, road object, etc) is represented as a node that also can be itself a group of nodes. They are logical and spatially grouped in subgraphs to improve rendering performance. Furthermore, OSG is cross-platform and enables the possibility to install our driving simulator in different operating systems. Figure 6.8 shows the architecture of the OSG.

The `osg` library provides the basic scene graph classes such as Nodes and Drawables. While the `osgDB` provides support for reading and writing scene graphs. We use this library to import the 3D object files that compose the scenarios used in our simulations. It includes different plugins for loading 3D objects, including COLLADA, LightWave (.lwo), Alias Wavefront (.obj), 3D Studio Max (.3ds), AutoCad (.dxf) and of course the .osg format. Scenario objects such vehicles, roads, buildings, trees, are represented as nodes by OSG. These nodes can be: objects from the VANET simulator; and objects created by the driving simulator itself. The driving simulator matches the type of each object that receives from the VANET simulator with its correspondent 3D objects from the database. This support is crucial to test applications that use all sorts of vehicles, such as trucks or bikes. Furthermore, our driving simulator must be capable of simulate large scale scenarios, such an entire

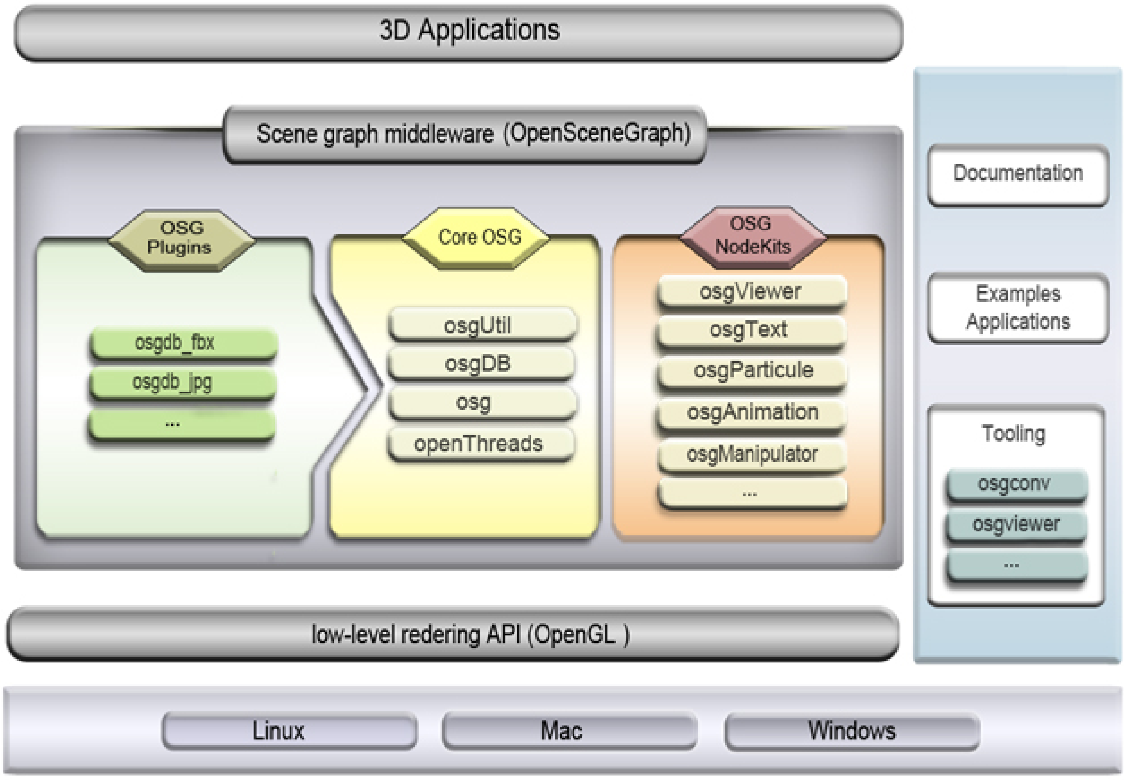

Figure 6.8: Architecture of the OSG by [3].

city. We use several techniques to improve performance on these type of scenarios, such as view-frustum culling, occlusion culling and Level Of Detail (LOD) nodes. The `osgViewer` library provides functionalities to make it easier to write different types of viewers of the scenario. This library is responsible for showing the perspective of the driving vehicle inside the scenario. Furthermore, we use this library to combine all the different views of the scenario, as the front-view, rear-view and side-views. This flexibility allows to access not only to the views of the driver's vehicle, but also to the views attached to each vehicle in the scenario, which is particularly useful for testing the STS.

We use the Bullet Physics Engine [150], an advanced physics engine that helps to build up a realistic driving experience and have a correct vehicle dynamics. Bullet is an open source physics engine written in C++ and it is largely used by film and game companies. We use the osgBullet library [152] to integrate the Bullet with the OSG. We apply physics to every single node of the scenario in our driving simulator. Vehicles that can be driven have their own personal parameters that affect physics, not only regarding its shape and weight, but also its dynamics. For each one of these vehicles we define its centre of mass, suspension parameters, engine force, power curve and number of gears. Table 6.2 shows the

Parameter	Value
mass (Kg)	800
maxEngineForce (N)	1000
maxBrakingForce (N)	100
steeringIncrement	0.04
steeringClamp	0.3
wheelFriction	30
suspensionStiffness	20
suspensionDamping	2.3
suspensionCompression	4.4
rollInfluence	0.1
suspensionRestLength	0.6

Table 6.2: Default parameters for the physics' dynamics of a vehicle.

default parameters for a vehicle. All of these parameters change accordingly with type of the vehicle.

We use the Logitech G27 steering wheel [153] as the HMI for the interaction with the driving simulator. Parameter tuning was performed to match the steering from the steering wheel with the steering values in the simulator. The usage of speeding and braking pedals was also subject of tuning, so that the driver can apply the correct engine and braking forces.

6.3.6 Driving Simulator Execution

In the Section 6.3.4 we illustrate the simulation execution of the Driver-Centric VANET Simulator framework. However, this execution only focus on the synchronism between the two simulators that comprise the framework. Internally, the driving simulator also must perform its own synchronism at each step. Figure 6.9 illustrates each simulation step, which visually represents each frame seen by the driver. Each simulation step is executed thirty times per second.

In each step we update the position of the vehicles provided by the VANET simulator, eliminate the vehicles that no longer are in the surroundings and create the new vehicles. Next, the driving step is executed, capturing all the interaction from the driver. The physics step is responsible to calculate the physical changes caused by the previous steps. Finally, the scene step observes the scene graph and subgraphs and calculates the nodes that will be rendered by the viewer. To a better performance, the viewer only renders objects that are in the vision field of the driver, and continuously monitors the level of detail of the nodes.

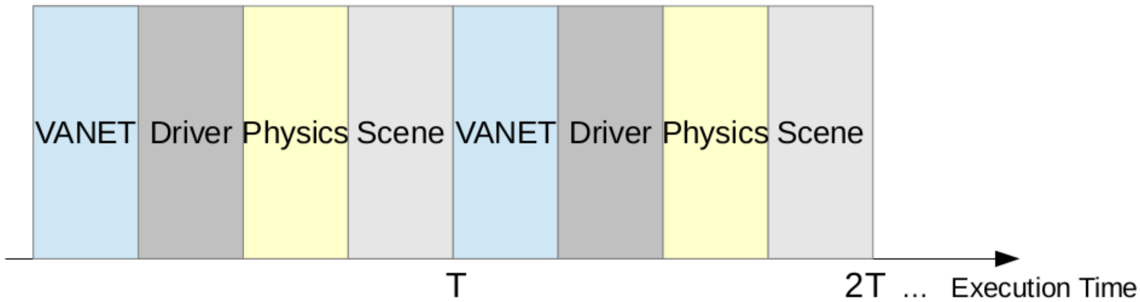

Figure 6.9: Simulation execution step of driving simulator.

Thus, we can assure that in each rendered frame all displayed vehicles and objects from the VANET simulator are correctly positioned in the scenario, as well as the changes made by the driver affect both scene and physics.

6.4 Simulation Platform Applicability

In this section, we present the Driver-Centric VANET Simulation framework applicability by presenting two applications that were evaluated within this platform. Since our approach proposed the creation of a simulation tool to reproduce real traffic conditions in a driving scenario, we designed the Driver-Centric VANET simulation according to the usability heuristics for users interfaces suggested in [154]. Furthermore, we performed a preliminary usability inspection during the design phase that allowed us to correct possible problems in the user interface to further work on a more detailed usability study in future projects. During the inspection, issues related to animation and artwork could be improved. In addition the grade of accuracy of the system in terms of damage, physics, and control was increased.

We think that the Driver-Centric VANET simulation tool provides the right framework to validate VANET-based applications in the inter-vehicle communication context due to its capacity to model realistic traffic condition scenarios. Two examples for such VANET-based driver information systems tested using our driving simulator are described below.

6.4.1 See-Through System

In the Section 4.1.1 we presented the STS, a cooperative ADAS for the overtaking manoeuvre over vision-obstruction vehicles. Testing the STS in a real-world situation safety issues regarding possible driver distraction or system delay can arise due to the nature of the application, thus resulting in possible crash situations. Therefore, our driving simulation framework is the perfect platform to test different approaches to the STS and evaluate if such approaches are feasible and if the are ready to be tested on the road.

6.4.1.1 Version 1.0

In the first approach of the STS, the view from the preceding vehicle equipped with the system is displayed in the dashboard. We used our simulation framework to evaluate this first approach and designed a scenario with a straight road with a total length of 1 km, with two lanes similar to the country roads. Each simulated vehicle has a camera attached to its front windshield. However for the STS we defined that only vision-obstructing vehicles with the STS enabled can share their perspective. We designed a simple dashboard that is similar to the Smart car [149] and put a simple LCD placed in front of the driver. When the driver activates the system this perspective is accessed and embedded in the LCD placed on the dashboard.

To test the usability of the system through this simulator we resorted to 20 drivers recruited at the Faculdade de Ciências da Universidade do Porto (FCUP) covering a range of ages between 20 and 65. Every person runs the tests six times to reach a certain training effect and to be familiarized with the simulator and the STS. Half of the runs are performed using the STS and half of them without using it. The experiment consists on driving the given road scenario and trying to arrive as soon as possible at the destination, respecting all the traffic regulations. Trucks are programmed to drive slowly so that overtaking is enforced. We measure the time that a test person needs to drive from the starting point to the destination point, with and without STS. Before starting the experiment an overview of the system was provided to the participants. After the task, the participant completes a post-task questionnaire that addresses questions related to the usefulness of the system. The time it takes to reach the destination determines the driving performance of the participant. The experiment showed that a certain experience with test driving in simulators is required to reach the minimal required performance.

Figure 6.10 depicts the results of this experiment. It shows a significant decrease of time to the destination with the STS compared to not having it. In addition, 90% of the participants considers that the STS makes it easier to overtake other vehicles and the totality of them regarded the information provided by the STS as useful. Thus, these results show that in fact the STS facilitates the overtaking manoeuvre by providing a better perspective of the road ahead.

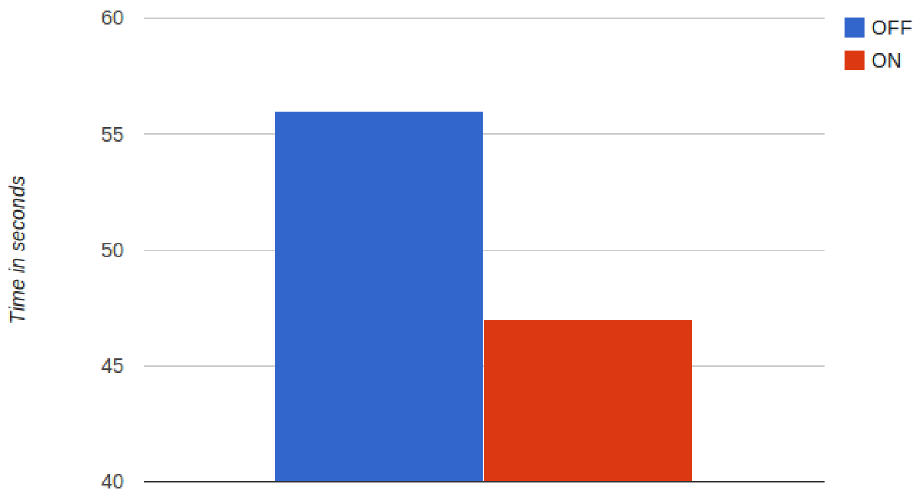

Figure 6.10: See-Through System 1.0 experience results.

6.4.1.2 Version 2.0

The second iteration of the STS, instead of using the dashboard it projects the view from the preceding vehicle on the windshield. Thus, reducing the eye glance time that the first version of the STS needed to observe the view. The driving simulator allowed to analyse the feasibility of this version. As in the previous version, when the system is activated by the driver, the view from the preceding vehicle is accessed and shown to the driver. However, instead of displaying in the dashboard, we project this image on the rear of this vehicle. In the first test, we detected that simply overlaying the view on the rear was not enough. With such approach, we suffer from the lack of depth perspective regarding the length of the preceding vehicle. Thus, we introduced a frame that embeds this view that has in consideration all these parameters. Section 4.1.2.2 shows how this frame is calculated.

This approach can bee seen tested in our simulation platform in the Fig. 6.11. Frame a) shows the truck with the STS disabled, where frame b) shows the system activated. As mentioned before, the STS is designed to help in the cognitive process of overtaking vision-obstructing vehicles through the use of the opposite direction traffic lane. With the OSG library it is simple to define the placement and angle of view of different cameras capturing the scenario and getting their respective visual scope. For the STS simulation we setup two cameras: one capturing the perspective of the vehicle being driven by a participant in the STS usability evaluation; and the other with the visual perspective of the preceding vehicle that cooperates with the request of STS.

The interaction with the system takes place through a manual press control that can be

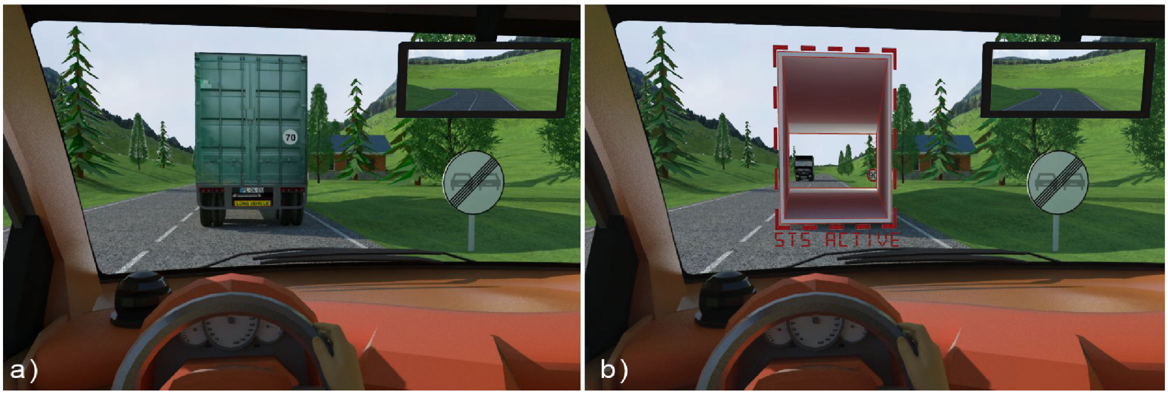

Figure 6.11: See-Through System evaluation in the context of our driving simulator.

activated or deactivated depending on the need. Figure 6.4 shows the interaction between the in-vehicle simulator that consists on a cockpit-level simulator and a VANET simulator, incorporating the physical real car frame and the virtual scenarios stored in a database.

The simulated scenario consists of a circuit with four curves with a total length of approximately 5 km in which each straight line has approximately 1 km. It represents two lanes: the cruising lane (on the right side) and the passing lane or lane for overtaking (on the left side). Figure 6.12 illustrates the circuit used for the simulation and a partial view of the 3D scenario without vehicles. We use realistic graphics to implement the 3D road scenario that includes traffic signs, such as speed limits and permission/prohibition of overtaking vehicles. In addition the simulator is able to render potential damage, and offers the ability to change the vehicles and the scenario. The simulated vehicles include motorbikes, cars and trucks of different sizes, which have their own physics. The average speed of the simulated vehicles varies from 50 to 90 km/h being the average distance between cars 50 to 150 meters.

We ran some preliminary tests on our system to evaluate the usability of the passing assistant. We chose a sample of 5 persons with a driving licence to run the experiment. Every person drove in the simulated circuit during 10 minutes activating the passing assistant when necessary and during 10 minutes without activating it. Log files recorded the time that the experiment's participant spent behind a vision obstructing vehicle, a record of possible crashes and metrics related to the distance that the participant covered. The threshold value to the time spent behind such vehicle was 100 meters, precisely the distance at which the driver can activate the passing assistant. Preliminary results show that the average time that the participants spent behind a vision obstructing vehicle is 45% smaller when the passing assistant was activated than when it was not. The system was active an average of 1.6s. All participants considered that the STS makes it easier to overtake other vehicles and the information provided by the STS as useful.

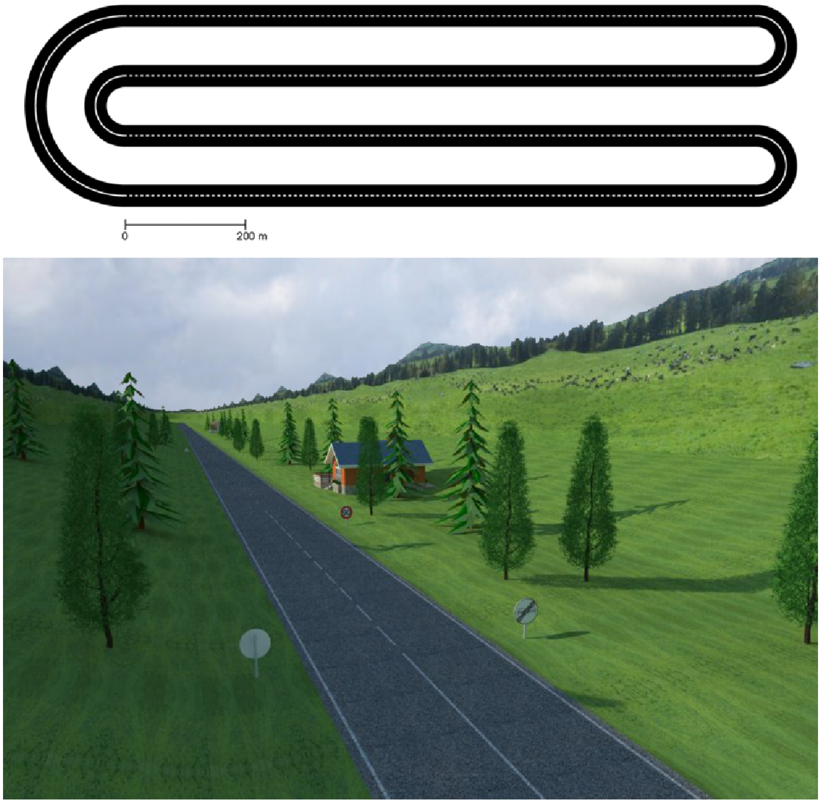

Figure 6.12: Circuit used for the usability evaluation of the passing assistant.

6.4.2 Virtual Traffic Lights

VTL will allow the migration of traffic lights as road-based infrastructures to in-vehicle virtual signs supported only by V2V communication [155]. When a crossing conflict is detected a need for a VTL arises. One of the conflicting vehicles acts as an intersection leader creating and controlling the VTL. This leader stops at the intersection and temporarily replaces a road-based traffic light in the control of the intersection. The fact that a person is operating a car simulated in the VANET environment provides us with the perfect scenario to perform tests related to the intersection lead. In addition our simulator allows us to analyse the VTL performance based on the number of vehicles in each intersection. The VTL approach means a radical change from the traditional way of controlling intersections through physical infrastructures. Thus a progressive process of the VTL deployment is required and a tool for experimenting with a partial deployment of the new technology that do not arise safety issues is crucial.

The Driver-Centric VANET simulator constitutes the perfect framework to measure the drivers' responsiveness to VTL projected on the windshield. It was used for a more extensive study of a GUI for VTL [20]. Our implementation adheres to the current design principles for in-vehicle information systems [156, 157, 158], and presents the driver with an intuitive user interface for traffic control that replaces the traditional traffic lights.

The main challenge of virtually representing traffic lights is to reflect the characteristics of the conventional traffic lights and make the transition to a new visualization process as smooth as possible. A good interface design complies with specific design requirements. In a driving environment, special attention has to be given to safety and usability. As a consequence of it, the interface has to be simple and easy to use without interfering with the primary driving task. This means that the time to recognize the displayed information has to be as short as possible. Additionally the information conveyed by the HMI has to reflect the outside real world traffic conditions. A good visibility needs to be ensured with a good luminance contrast of the displayed information, brightness and contrast. In addition the use of sun glasses or weather conditions (e.g. bright sun) need to be taken into account as well as the best possible location of the user interface.

Since the very first traffic light installation people had to go a long way to get used to the traffic lights and to obey them. The transition of Physical Traffic Lights (PTL) to VTL has to follow a slow process that gives the driver the chance to progressively adapt to the new concept. Following same design elements of physical traffic lights in terms of the aspects mentioned in [159], we state these main characteristics for VTL:

- **Design:** We used a HUD to project the virtual object on the vehicle's windshield. Since a small amount of information has to be conveyed, this representation scheme is ideal to display the few elements required in this particular situation. The images used in the projections correspond to a real road environment and displayed signs representing traffic lights ahead, arrows and traffic lights. Since we use unfamiliar symbols a text label showing the distance to the intersection completes the information provided to the driver according to the specifications in [156].
- **Placement and Operation:** Following the specifications in [156] we projected the VTL information 2.5 to 4 meters away from the driver's eyes in his field of view.
- **Maintenance and Uniformity:** Due to the electronic nature of the system's implementation to display the VTLs, the maintenance is similar to the other electronic components in the vehicle. In addition, the installation of the sensors and the V2V communications enables a similar functioning of all the traffic lights virtually displayed in every vehicle.
- **Color Code:** Luminance contrast requirements were followed to ensure that there was no visual interference with the road traffic environment and that the projected images were visible in all weather conditions.

- **Symbols used:** The VTLs should be functional in situations where an adequate stopping sight distance at the intersection is not available. This is the case that applies when physical infrastructures that are visible to the driver as a reference point are non-existent. Therefore, the VTL approach displays a traffic light ahead warning sign, so that the driver has information about an approaching intersection. Figure 6.13 shows the proposed GUI for the VTL. Through the windshield projection of the traffic lights, the driver is able to see the traffic light's state during the process of approaching and leaving an intersection. This characteristic makes our approach unique, since it prevents situations where the field of view of traffic lights mounted on the road can be obstructed by objects. The distance of placement of signal ahead signs are determined by the vehicle speed, the legibility distance, and the vehicle's manoeuvres time [159]. In Portugal this distance varies between 300 and 150 meters [160]. According to this, a traffic light ahead sign was displayed on the windshield at a distance of 200 m before the intersection.

- **Signal Timing:** This VTL system assures an effective response to changes in traffic conditions through a robust detection system. Additionally, the traffic light phase awareness allows warning the driver if a traffic violation occurs. Each vehicle maintains an internal database with information about intersections where a VTL can be created. When approaching such intersections, if a VTL message is detected, the current state of the VTLs is presented to the driver through the in-vehicle display. Our detection system bases on beaconing and location tables features of VANET geographical routing protocols, such as Geocast [161]. When vehicles are approaching intersections and do not detect VTLs' messages, they consult their location tables and the road map topology to infer crossing conflicts that will give rise to the collaborative creation of a VTL. We assume lane-level accuracy on the location tables and a common digital road map that also has lane-level information of topology.

Figure 6.13 shows two different user interface design solutions. In the frame A, the image represents the interface through the traffic light ahead sign and driving priority through green, yellow or red coloured arrows. Frame B shows the traffic light ahead, driving priority and driving permission through a traffic light image.

This GUI was complemented with a sign displaying that there is an intersection ahead. This sign can be seen in Fig 6.14.

6.4.2.1 Driving Performance Metrics

We determined the most relevant metrics to identify possible negative effects of our GUI for VTL in the driving performance. These metrics are applicable in the scenario where the

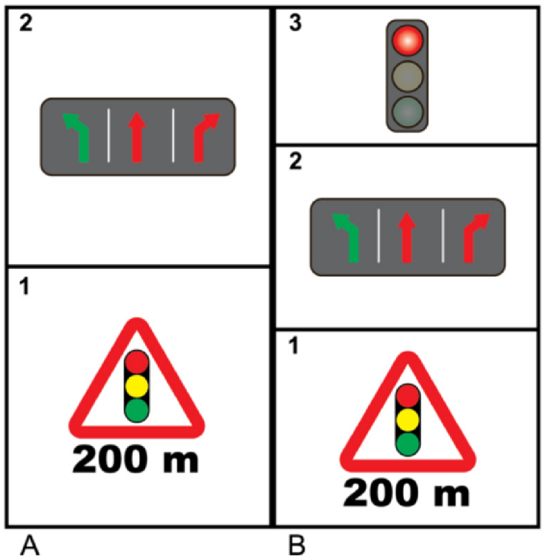

Figure 6.13: Virtual Traffic Lights' GUI.

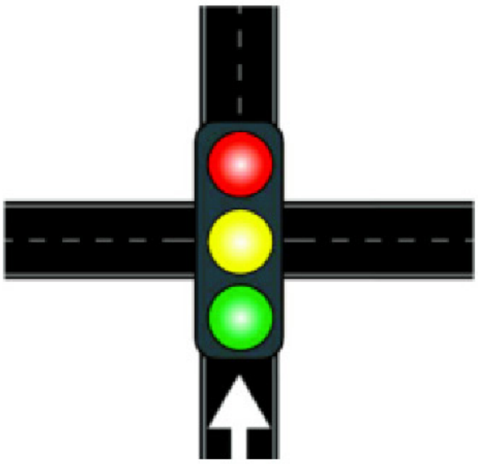

Figure 6.14: Sign representing an intersection ahead.

traffic lights are more frequently used, namely, an urban scenario. The most commonly used metrics in driving performance studies are speed metrics that determine the speed reducing effects of traffic signs in road intersections. Thus, speed variation and brake activity are the most applicable metrics in our scenario. The speed variation determines the variation of speed in a situation that requires the driver to adapt the vehicle's velocity to new road circumstances such as the existence of a traffic sign or an intersection. The brake activity determines the driving performance in situations where the driver has to respond quickly to a road circumstance. The simulator conditions of our experiment test allow us to define and represent an accurate event that will cause the desired braking reaction, namely to switch the traffic light to red. In our experiment we use identical onset events for different subjects. The metric is a straightforward metric of driving performance on a regulating or monitoring level [162].

To evaluate the driving performance we first defined the events that cause a variation in the speed. These events are applied in the same way for each participant. The experiment consisted on driving through a predefined path without secondary tasks in a medium to high traffic density without critical events. We logged the indicators that caused variation in the scenario: a red traffic light; the speed; and distance to intersection. Brake activity was calculated through the usage of the braking pedal or by the deceleration change rate by measuring the speed change. Additionally we collected driving performance data and subjective ratings through a post task questionnaire. The simulation duration and starting point was the same for all the participants. It allowed comparing every point, overlapping similar speed data sections and determining differences in the speed variation.

6.4.2.2 Experiment Setup

The participants were given a short explanation about the experiment procedure and purpose, and were indicated to drive as usual and respecting traffic laws. During a training session with no data logged, each participant drove one lap through the circuit driving accordingly to the traffic lights. After this familiarization with the simulation tool, the participants were asked to drive through the predefined path. In the early stage test phase different user interface design approaches were compared. The participants in this phase drove once using a user interface and once using a different one. In the summative evaluation phase, we used two scenarios: one with regular PTL; one with the VTL. The PTL in our scenario complied with standard regulations, being visible to the driver from a distance of 80 meters at a speed of 50 km/h and a distance of 35 meters at a speed of 20 km/h [163]. The speed limits in our scenario were 50 km/h. Accordingly, the stopping sight distances were 65 meters. The participants in this evaluation tested both approaches. Finally the participants were asked to fill in an online post task questionnaire, asking for demographic information and subjective rates.

We created a scenario specifically designed for testing the VTL. Figure 6.15 shows the driving scenario used for the evaluation of the HMI for virtually representing traffic lights in the car. The frame at the top shows a 3D view of the whole scenario without vehicles. The frame at the bottom gives an overview of the circuit used to perform the experiments. The scenario consisted of one road in the shape of an eight with a range of two to three lanes and had one intersection. This shape allows to drive continuously and cross the intersection

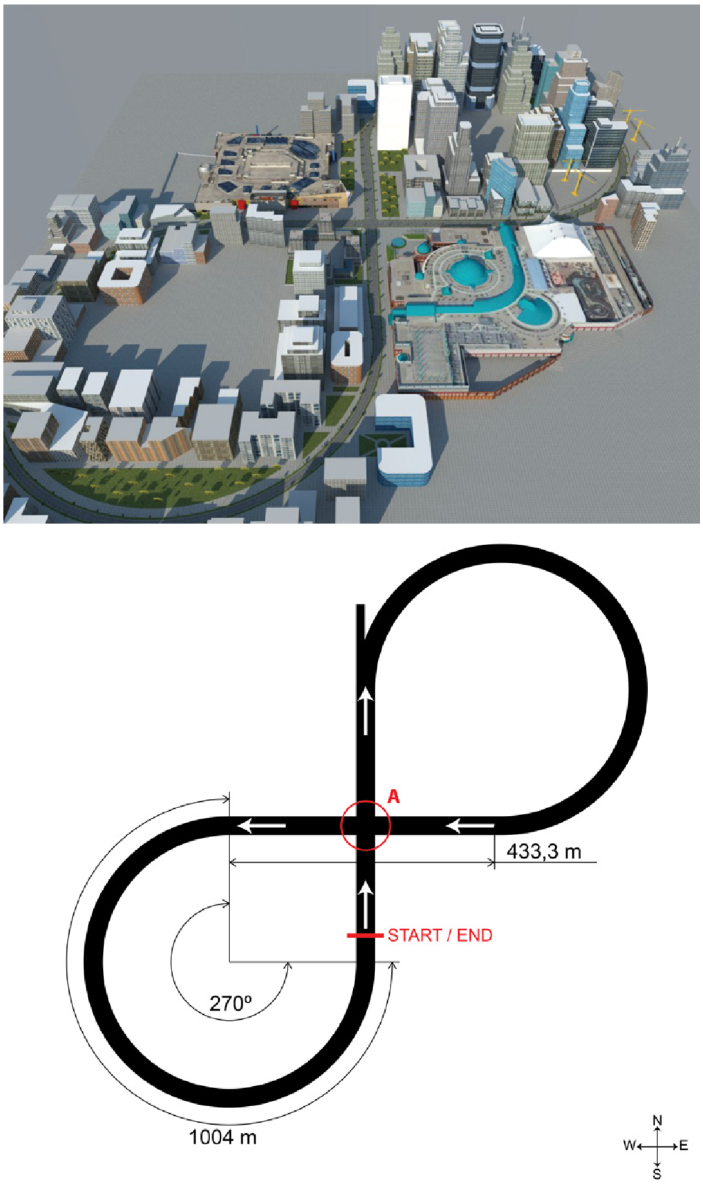

Figure 6.15: Driving scenario used for testing VTL.

several times. The total length of this scenario is 2874 meters, with two straight sections with approximately 433 meters. The vehicles included in the scenario were cars and trucks of different sizes. The velocities of the cars in our urban scenario varied from 20 to 50 km/h. A speedometer showed the speed of the car's participant.

The scenario's road signs and markings were designed according to the rules from the Portuguese Road Infrastructure Institute (INIR). In particular we considered the norms for road marks according to the dimensional characteristics, criteria of use and placement, and the norms for vertical signalling and its characteristics [164]. In the PTL scenario, the traffic lights were located 2.5 meters high counted from the ground to the lower limit and 5 meters hight when placed over the road.

6.4.2.3 Stage Tests

To improve the human–centered design of the VTLs user interface, we performed a formative evaluation early in the design process. In this phase we compared different design solutions in the simulator framework. Six persons (3 male, 3 female, average age class 27-35) where asked to participate in tests to compare two system designs (Fig 6.13). Next, we describe both designs:

1. First a graphical sign indicating a traffic light ahead is displayed with its correspondent distance label (200 meters) until arriving to the intersection. Alternatively, the driver was shown the image indicating an intersection ahead (Fig. 6.14). Next, a sign consisting of green, yellow or red coloured arrows is shown. This sign reflects the same behaviour than a conventional traffic light indicating the driving priority of the the driver and vehicles in the vicinity. The image is displayed in a range from 150 until 0 meters before the intersection and its size depends on the distance to the intersection.

2. This approach is similar to the previous one. However, in this case the arrows sign's displaying range is shortened to between 150 until 50 meters before the intersection. A sign representing a conventional traffic light that displays green, yellow or red is shown during the last 50 meters.

Figure 6.16 shows the proposed GUI inside the simulator.

Figure 6.16: VTL's GUI inside the driving simulator.

6.4.2.4 Summative Evaluation

We evaluated the GUI with respect to safety and user acceptance, and quantified the safety-reducing effects on the driving performance through the speed variation. As previously mentioned, we compared the performance with the VTL and with PTL. Regarding the driving performance, we logged the speed data points and braking pedal activity to get the speed variation and braking performance respectively. Additionally, we recorded the traffic light state. This data was automatically evaluated after a previous manual control and filtering process.

Every participant performed the tests twice, once with the VTL and once with the PTL. Thus, the groups were related to each other and the samples were dependent. To find out whether the use of a system had an effect on the brake activity of the driver, we applied the T-Test for dependent samples. We then compared the actual difference in means between the VTL and the PTL groups on the deceleration rate. To ensure a representative sample for the experiment we selected 10 participants (5 male, 5 female, average age 35) with a driver experience 6 and 10 years. Every person ran two laps through the circuit with the VTLs and with the PTL, logging a total of data related to eight traffic lights for each person.

6.4.2.5 Preliminary Evaluation Results

The data resulting from the early stage tests helped to improve the human-centered designed of the VTLs user interface. Since 100% of the participants agreed that the sign indicating a intersection ahead was not intuitive enough (Fig. 6.14). Therefore, we redesigned the interface with the sign indicating traffic light ahead with the distance to the intersection (Fig. 6.13). Further tests with these two approaches indicated that the second reflected the idea of a traffic light in a more intuitive way. This was confirmed by the 83% of participants that considered the three stage GUI to be simpler and easier to understand. Nevertheless, none of the designs were considered dangerous or unsafe by anyone. The VTL's GUI was classified as clear and intuitive by 90% of participants. They did not find the system distracting or unsafe.

Regarding the brake activity, the deceleration change rates slightly differed between VTL and PTL. However this difference considering the brake pedal activity was not significant. Regarding the speed variation metrics, no differences could be determined in the performance with each system. As expected a high variation regarding the speed was observed depending on the participant. The driving performance did not significantly differed from the experiment with the VTL and the one with the PTL. In the future, a more extensive and complex study must be performed. An experiment with a high number of participants will allow to prove the equivalence between the two systems and that there is no practical consequences on using the VTL instead the traditional PTL.

6.5 Conclusions

By making it possible to implement a diversity of scenarios, the Driver-Centric VANET Simulator proved to be the perfect tool to test innovative driver information systems. Our driving simulator, has successfully been used to test two innovative applications. The testing of the STS using simulation was crucial to detect possible system's design flaws that could cause safety issues. Moreover, it was possible to study one of the possible solutions for the VTL, even though the study only had few participants.

Chapter 7

Conclusions

The main goal of this thesis was to design the next-generation driver information systems that improve safety and sustainability of the vehicular transportation. This thesis work envisioned the use of vehicular communications and augmented reality to enable safer and innovative intelligent driver information systems. We presented the STS, a cooperative ADAS for overtaking manoeuvres of large and vision obstructing vehicles that leverages the unique characteristics of DSRC, which allows very low latency video streaming between two vehicles. This system uses a sophisticated HMI based on augmented reality, which seamlessly transforms the vehicles being overtaken into transparent tubular objects. We showed that the augmented reality aspect of the STS is indeed representative of the overtaking scenario physical characteristics, thus providing an intuitive driver assistance system. We successfully prototyped and implemented the STS using a transparent LCD as the HCI to deliver the system to the driver. Furthermore, the STS was also implemented using the Vuzix® augmented reality glasses. This system gathered a huge attention and acceptance from the worldwide media, generating a number of articles and video visualizations, proving the acceptance as an ADAS capable of improving the safety of overtaking manoeuvres. We presented the CVCAM, a system that leverages the same concept of the virtual windshield for display information about the surroundings of the vehicle. This system envisions the usage of vehicular communications coupled with computer vision to provide information about neighbouring vehicles, which is useful for situations with reduced visibility. Regarding safety, we also proposed the VSS a system that makes use of vehicular communications to trigger audible events to warn the user for events happening in his surroundings. VSS can be used to for alert the driver of sudden emergency brake situations or for the presence of emergency vehicles.

Regarding sustainability of vehicular transportation, we explored two different areas: the road infrastructure; and public transportation systems. We presented a scheme for funding road infrastructures using advertising, V2I and augmented reality, introducing the concept of the virtual billboard. We studied how road infrastructures were funded and presented a system that can eliminate tolls on highways by displaying advertisements directly on the windshield. This system merges the concept of advertising funding schemes for Internet websites with the roadside billboards placed along the highway. Furthermore, we presented an advertising delivery platform for public transportation systems. This platform has a hybrid approach that relies on cellular and vehicular communications for delivering advertisements to a taxi. We focused on the reduction of costs related to cellular communications and explored different approaches to deliver advertisements. We performed an evaluation of this advertising delivery platform and compared the performance of each solution using a real dataset. Moreover, we presented the reduction of the costs that this platform can provide to such type of transportation system.

This thesis also focused on providing a framework that permits to evaluate VANET-enabled driver information systems using simulation. We developed a driving simulator integrated with a VANET simulator that is capable to provide different type of scenarios. We proved the framework applicability by implementing and testing two different VANET-enabled applications, that we would not be able to test on public roads.

7.1 Future Work

Future will be largely based on the concept of the virtual windshield that can be the basis for the future driver information systems. In the future, a partnership with an automotive company is being prepared in order to implement such systems and other VANET and AR enabled related applications and services in actual vehicles.

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